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DEVELOPMENT OF A CONSEQUENTIAL DYNAMIC MODEL INCORPORATING VARIABILITY AND UNCERTAINTY ANALYSIS FOR ASSESSING LIFE CYCLE ENVIRONMENTAL IMPACTS OF PAVEMENTS

DÉVELOPPEMENT D'UN MODÈLE DYNAMIQUE INCORPORANT L'ANALYSE DE LA VARIABILITÉ ET DE L'INCERTITUDE POUR L'ÉVALUATION DES CONSÉQUENCES ENVIRONNEMENTALES DU CYCLE DE VIE DES CHAUSSÉES

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This work is dedicated to my family.

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RÉSUMÉ

Le choix d’une option écologique pour les chaussées parmi plusieurs options constitue un défi pour les gouvernements depuis longtemps. Une quantité importante de matériaux est requise pour la construction des chaussées et le maintien des conditions de service de la circulation au-dessous des seuils de performance. Afin de répondre à la demande en matériaux de construction, des procédés énergivores doivent être mis en place. Ces procédés produisent différents types d'émissions. En outre, il convient de noter que les impacts environnementaux des chaussées ne se limitent seulement pas aux matériaux de construction et aux machines. En effet, la sélection d’un type de chaussée peut influencer, selon ses propriétés, la consommation de carburant des véhicules et les demandes en climatisation des bâtiments avoisinants.

Jusqu'à présent, plusieurs impacts environnementaux de matériaux alternatifs pour la construction de chaussées ont été étudiés grâce à la méthode d'analyse du cycle de vie (ACV). Lors d'une ACV de chaussée à grande échelle, visant à examiner les implications ou exigences liées aux politiques, par exemple, il est important d'évaluer les changements induits sur le marché par ces politiques. Ces changements peuvent concerner une modification de la demande pour d'autres produits ayant la même fonction et / ou du volume des coproduits générés. L'ACV conséquentielle (ACVC) est utilisée pour saisir les conséquences environnementales directes et indirectes de la sélection des chaussées. Des études antérieures d'ACVC ont identifié les technologies affectées à long terme dans des phases distinctes du cycle de vie du produit. Les résultats de ces études tendent, cependant, à négliger les impacts des systèmes de produits à court terme. En fait, le manque de comptabilité dynamique dans les études d'ACVC empêche les décideurs d'obtenir une analyse plus complète et mieux informée des flux d'émissions au fil du temps. De plus, compte tenu de la longue phase d'utilisation des infrastructures routières, un grand nombre de paramètres interdépendants change constamment en fonction du temps.

Une structure dynamique devient alors essentielle pour relier ces paramètres aux facteurs de caractérisation (FC) dynamiques. De plus, l'application des facteurs d'émission et des changements dans la consommation de carburant ou de l'efficacité peut aider à améliorer la précision du processus décisionnel lié à la sélection des chaussées. Cependant, la distribution temporelle des impacts, induits par les paramètres du cycle de vie de la chaussée, n'est pas

entièrement prise en compte dans les études précédentes d'ACVC. Les incertitudes et les variabilités doivent être étudiés pour examiner la robustesse des résultats, ce qui n'a pas encore été pris en compte auparavant en ACV. Pour élaborer un cadre plus global dans l'analyse des incertitudes et des variabilités, il est essentiel de considérer les dépendances réciproques entre les sources de variabilité et d'incertitude. En fait, négliger ces interdépendances peut mener à une conclusion entièrement différente de celle obtenue par un échantillonnage indépendant. Jusqu'à présent, aucune méthode n'a été proposée pour évaluer de manière cohérente les sources de variabilité et d'incertitude des ACV de la chaussée, que ce soit dans des contextes conséquentiels ou attributionnels.

Le premier objectif de ce projet de recherche vise à développer un cadre global, capable de capturer les interdépendances des paramètres tout en analysant les sources d'incertitude et de variabilité. Le cadre proposé comprend des simulations de Monte Carlo pour la propagation des incertitudes et de différents types des variabilités. Le cadre a été appliqué à une étude de cas d'ACV attributionnelle (ACVA), dans laquelle l'asphalte et le béton ont été comparés. Différentes sources, telles que l'incertitude due à la qualité des données et aux choix méthodologiques ainsi que la variabilité des paramètres, ont été étudiées.

Les résultats de l'analyse de Monte Carlo montrent que les choix méthodologiques, telle que la méthode d'allocation, peuvent modifier le scénario le moins impactant sur l’environnement pour quatre catégories intermédiaires. Ces catégories sont principalement affectées par la chaîne d'approvisionnement en pétrole brut. La variabilité des matériaux et des méthodes de construction peut modifier le scénario préféré dans différentes catégories de dommages, à savoir la santé humaine et le réchauffement climatique. En outre, le scénario préféré en matière de qualité de l'écosystème peut être modifié lorsque l'incertitude des paramètres est prise en compte. La raison en est que les scores qualitatifs les plus mauvais sont donnés à l'incertitude géographique du flux élémentaire qui contribue majoritairement à la qualité de l'écosystème (c'est-à-dire le zinc). L'effet combiné des sources d'incertitude et de variabilité pour cette étude de cas empêche le décideur d'en arriver à une conclusion robuste sur la qualité de l'écosystème, la santé humaine et les effets du réchauffement climatique. Cependant, pour la catégorie ressource, le résultat comparatif entre la chaussée en asphalte et en béton est suffisamment important et, par conséquent, les sources de variabilités et d'incertitudes ne changent pas les conclusions.

Le second objectif de ce projet de recherche est de développer un cadre de travail dynamique pour l'évaluation de l'aspect environnemental des chaussées. De plus, le cadre proposé dans le premier objectif a été adopté pour considérer diverses sources d'incertitude et de variabilité, tels que la qualité des données, les paramètres de modélisation et la variabilité, dans différentes phases du cycle de vie des chaussées. Les changements dynamiques du vecteur de la demande et de la matrice de la technosphère ont été calculés en tenant compte de l'horizon temporel dans lequel les technologies sont affectées. Les composantes du cycle de vie ont été délimitées grâce à une paramétrisation précise de plus de 130 facteurs dépendant du temps. Selon le cadre d'analyse des incertitudes proposé à l'étape précédente, une simulation de Monte Carlo a été menée pour propager les incertitudes et les variabilités du système en divisant les paramètres par l'incertitude de qualité des données, l'incertitude de modélisation et la variabilité des données. La méthode proposée a été appliquée à l'étude de cas d'une chaussée en asphalte (Statu quo) changé en chaussée en béton (choix alternatif).

Les résultats montrent qu'une simplification de changements dynamiques dans l'ACV des chaussées peut entraîner une évaluation inexacte des résultats de dommages. Les avantages environnementaux attribués en substituant le scénario du statu quo par l'alternatif sont alors surestimés de 7, 17 et 77% pour respectivement les catégories changement climatique, santé humaine et ressource. En outre, les résultats de la catégorie qualité des écosystèmes montrent que la modélisation dynamique peut avoir un impact supérieur de 114% à la mise en œuvre de l'approche statique. Le manque de prise en compte du profil temporel des émissions de gaz à effet de serre dans les résultats, avec des FC statiques, conduit à une surestimation de 473,5 t CO_{2eq} des bénéfices du potentiel de réchauffement climatique lors de la substitution de l'asphalte au béton. Les résultats d'incertitude montrent que les sources de variabilité contribuent à 41-71% de la variance des quatre catégories de dommages. Cette contribution est principalement attribuée à la comptabilisation mensuelle de la température (8-16% de la variance des résultats de dommages) et à la durée de vie des chaussées (11-15% de la variance des résultats de dommages). Malgré la propagation des diverses sources d'incertitude et de variabilité dans cette étude de cas, la conclusion sur le scénario préféré est demeurée inchangée dans les résultats des dommages.

Ce projet de recherche a clairement montré l'impact de la prise en compte des changements en temps réel dans l'évaluation environnementale de la chaussée. Plus précisément, en ce qui concerne la phase d'utilisation et les horizons temporels de la technologie affectée, il est essentiel d'inclure les variables dépendantes du temps pour améliorer la représentativité des résultats obtenus. Néanmoins, l'importance des sources d'incertitude et de variabilité et de leur distinction dans l'ACV de la chaussée ne doivent pas être ignorées.

Mots clés: Chaussées, Analyse du cycle de vie (ACV) conséquentielle; Analyse d'incertitude; ACV attributionnelle; Inventaire dynamique; Effets indirects; Politique environnementale.

SUMMARY

The selection of an environment-friendly alternative for pavements remains a challenge for governments for a long time now. A significant quantity of materials is required for the construction of pavements and maintenance of traffic service conditions above the performance thresholds. In order to meet the demand for construction materials, energy-intensive activities must be operated, which produce various types of emissions. Further, it should be mentioned that the environmental impacts of pavements are not limited to construction materials and machinery. In fact, pavement selection can induce changes in fuel consumption of vehicles and, to some extent, can adjust the heating and cooling demands of buildings through the properties of pavements.

So far, several environmental impacts from alternative materials for constructing pavements have been investigated through the method of life cycle assessment (LCA). Conducting LCA of pavement on a large scale, such as, when considering its policy-related implications or requirements, is distinguished from small scale assessment. In the large-scale assessment, it is important to assess the changes induced through the demand of other products with the same function and/or the induced production volume of the co-producing processes. Consequential LCA (CLCA) is employed to capture the direct and indirect environmental consequences of pavement selection in different sectors. Previous CLCA studies have only captured the long-term affected technologies in distinct phases of the product life cycle. Hence, the results tend to neglect the short-term impacts and the impacts of short-run product systems. In fact, the lack of dynamic accounting in CLCA prevents policymakers from gaining a more informed and comprehensive analysis of emission flows over time. Furthermore, given the long use phase of pavement infrastructures, the vast number of interdependent parameters constantly change as a function of time. A dynamic structure is essential to link these parameters to dynamic characterization factors (CFs). Moreover, apart from being complex and requiring the prediction of technological improvements, applying the emission factors and fuel consumption or efficiency improvements can help enhancing the accuracy of the decision-making process involved in the selection of pavements. However, the temporal distribution of impacts induced by pavement life cycle parameters is not fully captured in previous CLCA studies. Moreover,

the variations of the results in CLCA studies are usually overlooked and are not included in the interpretation of the conclusions.

The uncertainty and variability sources should be investigated to examine the robustness of the results. To reach a comprehensive model for the uncertainty analysis, it is essential to consider the interdependencies of the variability and uncertainty sources. In fact, neglecting the interdependencies may lead to an entirely different conclusion compared to those obtained through an independent sampling. So far, no method has been proposed to consistently assess the variability and uncertainty sources of pavements LCAs either in consequential or attributional frameworks.

To fill in the research gaps, this dissertation aimed to develop a comprehensive framework, that is able to capture interdependencies of parameters while analyzing uncertainty and variability sources. The proposed model comprises Monte Carlo simulations to propagate the sources of variations to the results. The model was applied to a case study of attributional life cycle assessment (ALCA), in which asphalt and concrete pavements were compared. Different sources, such as uncertainty due to data quality and methodological choices as well as variability of parameters, were investigated.

The results of the Monte Carlo analysis show that it is feasible to assess the combined and the individual effects of common uncertainty and variability sources. Based on the variability and uncertainty of the results, a certain conclusion is case specific at both the midpoint and endpoint levels was identified. The methodological choices, such as allocation, can change the environmentally preferred scenario in four midpoint categories. The variability in construction materials and methods can change the preferred scenario in different damage categories, such as, human health and global warming. In addition, the preferred scenario in ecosystem quality can be changed when the parameter uncertainty is taken into account. The reason is that the worst qualitative scores are given to the geographical uncertainty of the elementary flow that majorly contributes to ecosystem quality (i.e. zinc). The combined effect of the uncertainty and variability sources for this case study prevents the decision-maker from reaching a robust conclusion about the ecosystem quality, human health, and global warming effects. However, for the resources category, the comparative result between asphalt and concrete pavements is sufficiently large. Therefore, the sources of variability and uncertainty do not change the preferred scenario.

The second objective of this research project is to develop a dynamic consequential framework for assessing the environmental aspect of pavements. Moreover, the proposed model in the first objective was adopted to assess various sources of uncertainty and variability, such as data quality and modeling and variability, in different life cycle phases of pavements. The dynamic changes in the demand vector and the technosphere matrix were computed considering the time horizon of the affected technologies. The life cycle components were delineated through a precise parametrization of more than 130 time-dependent factors. According to the uncertainty analysis model proposed in the previous stage, a Monte Carlo simulation was conducted to propagate the variations in the system dividing the parameters to data quality uncertainty, modeling uncertainty, and variability. The proposed method was applied to the case study of shifting from an asphalt pavement (business-as-usual) to a concrete one (alterative).

The obtained results show that a simplification for capturing the dynamic changes can result in an inaccurate assessment of the damage results. The environmental benefits credited by substituting the business-as-usual scenario with the alternative is overestimated by 7, 17, and 77% for climate change, ecosystem quality and resources categories, respectively. In addition, the results of ecosystem quality category show that including the dynamic spirit in the modeling can result in a 114% higher impact than implementing the static approach. The lack of accounting for temporal profile of the greenhouse gas (GHG) emissions in static CF results leads to an overestimation of the global warming potential (GWP) benefits of substituting asphalt with concrete by 473.5 t CO_{2eq}. The uncertainty results show 41-71% contribution of the variability sources to the variance of the four damage categories. This variability is mainly attributed to the monthly temperature accounting (8-16% to the variance of damage results) and the service life of pavements (11-15% to the variance of damage results). Despite propagating the various sources of uncertainty and variability in this case study, the conclusion on the shifting decision remained unchanged in the damage results.

This research project clearly showed the impact of considering the dynamic changes in the environmental assessment of pavement. More specifically, when it comes to the use phase and the time horizons of the affected technology, it is essential to include the time-dependent variables to improve the representativeness of the obtained results. Nevertheless, the importance of uncertainty and variability sources and distinguishing them in the pavement LCA should not be ignored.

Keywords: Pavements, Consequential life cycle assessment (CLCA); Uncertainty analysis; Attributional LCA; Dynamic inventory; Indirect effects; Environmental policy-making.

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LIST OF ACRONYMS AND ABREVIATIONS

Acronym	Definition
AA	Aquatic acidification
AADT	Annual average daily traffic
AEC	Aquatic ecotoxicity
AEU	Aquatic eutrophication
ALCA	Attributional life cycle assessment
ALT	Alternative
BAU	Business-as-usual
BFS	Blast furnace slag
C	Carcinogenic
CC	Climate change
CF	Characterization factor
CLCA	Consequential life cycle assessment
DALY	Disabled adjusted life years
DLCI	Dynamic life cycle inventory
EOL	End-of-life
EQ	Ecosystem quality
ELCD	European life cycle database
FHWA	Federal highway administration
FU	Functional unit
GHG	Greenhouse gas
GW	Global warming
GWP	Global warming potential
HH	Human health
HMA	Hot mix asphalt
IR	Ionizing radiation
IRI	International roughness index
ISO	International standard organization
JPCP	Jointed plain concrete pavement
kWh	Kilowatt hour
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment method
LO	Land occupation
ME	Minera extraction
M&R	Maintenance and repair
MTQ	Ministre des transports du Québec
NC	Non-carcinogenic
NE	Non-renewable energy
OLD	Ozone layer depletion
PDF.m^2.yr	Potentially disappeared fraction (on a certain surface and during a certain year)
R	Resources
RF	Radiative forcing

RI	Respiratory inorganic
RO	Respiratory organic
SCM	Supplementary cementitious material
TA/N	Terrestrial acidification and nitrification
TE	Terrestrial ecotoxicity
UHI	Urban heat island
USEIA	United States energy information administration
USEPA	United States environmental protection agency
USLCI	United States life cycle inventory

Published research communications from this dissertation

The doctoral work has resulted in two scientific papers published in peer-reviewed journals and another one submitted. Seven presentations were made in seminars and conferences in the form of oral (5) and poster (2). Details on all articles and communications are summarized in the following Table.

Type	**Details**	**Date**
Submitted article	Hessam AzariJafari, Ammar Yahia, Ben Amor; "Removing shadows from consequential LCA through a time-dependent modeling approach: policy-making in road pavement sector"; Environmental Science and Technology.	2018
Accepted article	Hessam AzariJafari, Ammar Yahia, Ben Amor; "Assessing the individual and combined effects of uncertainty and variability sources in comparative LCA of pavements"; International Journal of Life Cycle Assessment; (2017): 1-15.	2017
Accepted article	Hessam AzariJafari, Ammar Yahia, Mourad Ben Amor; "Life cycle assessment of pavements: Reviewing research challenges and opportunities"; Journal of Cleaner Production; Volume 112; Part 4 (2016): 2187-2197.	2016
Oral Presentation	Hessam AzariJafari, Ammar Yahia, Ben Amor; "Dynamic assessment of pavement rolling resistance and its environmental consequences: a case study of concrete and asphalt in Quebec"; Rencontres étudiantes du CRIB; June 2017; Sherbrooke; Canada.	2017
Oral Presentation	Hessam AzariJafari, Ammar Yahia, Murad Ben Amor; "Évaluation des impacts environnementaux des chaussées par le développement d'une nouvelle approche d'analyse du cycle de vie"; Forum Environnement et développement durable en Estrie; June 2017; Sherbrooke; Canada.	2017
Oral Presentation	Hessam AzariJafari, Ammar Yahia, Ben Amor; "Prediction of the environmental burdens associated with increased concrete pavement construction: a case study in Quebec"; ACI 123 Research in Progress Session, ACI Fall Convention, October 2016, Philadelphia, USA.	2016
Oral Presentation	Hessam AzariJafari, Ammar Yahia, Mourad Ben Amor; "Comparative life cycle environmental impacts of asphalt and jointed plain concrete pavement"; 22nd Annual CEGSS Conference; June 2015; Montreal; Canada.	2015
Oral Presentation	Hessam AzariJafari, Ammar Yahia, Mourad Ben Amor; "Comparative attributional life cycle assessment of asphalt and concrete pavements"; Rencontres étudiantes du CRIB; June 2015; Sherbrooke; Canada.	2015
Poster Presentation	Hessam AzariJafari, Ammar Yahia, Ben Amor; "Environmental friendly pavement selection in a context of macro-scale decision-making: A consequential LCA"; 5th International Forum on the Life Cycle Management of Products and Services (CYCLE 2016 in English); October 2016; Montreal; Canada.	2016
Poster Presentation	Hessam AzariJafari, Ammar Yahia, Mourad Ben Amor; "Life cycle assessment of concrete and asphalt pavements: a case study in the province of Quebec (Canada)"; LCA XV; Vancouver; October 2015; Canada.	2015

CHAPTER 1 INTRODUCTION

1.1 Context

The importance of environmental sustainability has been recognized in recent decades by public agencies and private contractors. Therefore, the stakeholders focus on the need to adopt ecological technologies and processes in life cycle stages of infrastructures. In transportation infrastructure, this focus is mainly put on environmentally friendly alternatives in the design, construction, operation, and maintenance of highways and driveways, including pavements. There are approximately 1.13 million two-lane equivalent lane-kilometers of public road in Canada [1]. Construction and maintenance of pavements requires large quantity of materials, which induces significant environmental impacts. Various construction materials used in pavements cause substantial environmental impacts (e.g., contributing approximately 75 Mt of carbon dioxide (CO_2) emissions, which is approximately 5% of the total transportation emissions in the U.S. [2]). Functional design of a pavement in cold regions requires thicker pavement layers to sustain frost heave and particularly uneven settlements at spring thaw. For example, roughly more than 5,300 t of asphalt (in case of asphalt pavement) and 1,900 m^3 of concrete (in case of cement concrete pavement) are required only for the surface layer of a 1-km highway in Canada [3]. In addition, preparation and transportation of the high volume of materials for pavement sub-layers and earthworks contribute to various environmental impacts.

Many sustainable practices have been implemented in pavements through innovative design and utilization of by-products. The increasing use of supplementary cementitious materials (SCMs) in concrete pavements cannot only recycle the waste material but also replace portland cement in the mix design. Long-life pavements are also designed to improve the environmental performance of highways through a long service life and minimum maintenance and repair (M&R). Although the consumption of construction materials is important in reaching an environmentally friendly decision, it is not the main driver of emissions in different parts of the world. In 2014, the road transportation sector emitted 142.6 Mt of CO_{2eq}, or 83.2% of transportation-related GHG emissions and 19.5% of total Canadian GHG emissions [4], which is principly attributed to vehicles fuel consumption and emissions. Similar contribution was reported in Quebec as shown in Figure 1.1 [5]. While governments focus on the GHG reduction solution such as car electrification, it has been already reported that pavements play an important role in the environmental impacts of road transportation [6, 7] through changing in rates of vehicles fuel consumption due to the rolling resistance at tire-pavement interface.

The environmental impacts of pavements are not limited to the transportation sectors as the physical properties of pavements can indirectly influence the energy consumptions in urban area as presented. In fact, the surface reflectivity of pavement can induce a radiative forcing (RF) effect and, consequently, change the ambient temperature in urban area. This change in temperature leads to an electricity adjustment for compensating heat gain or loss in buildings [8]. Therefore, a refined systematic approach for pavement systems is required to quantify the environmental impacts of the pavement systems during its whole life cycle, including the usage stage.

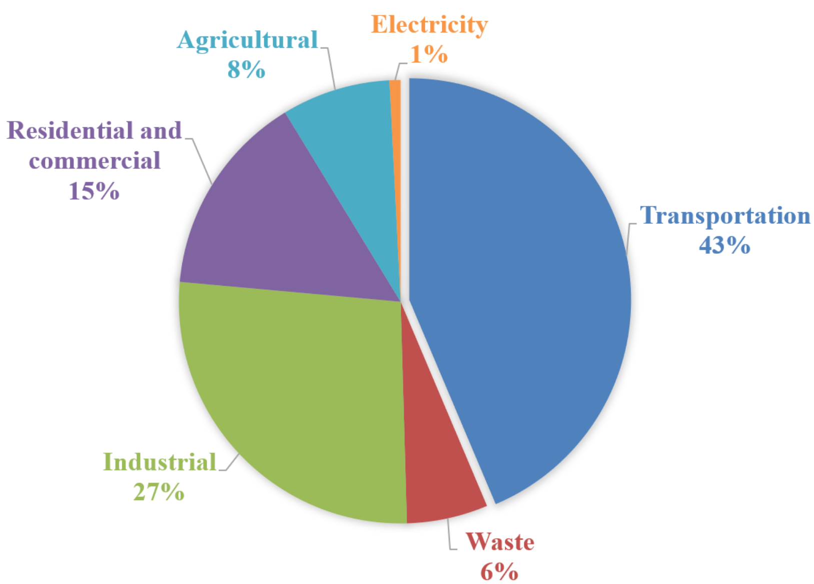

Figure 1.1. Contribution of different sectors to GHG emissions in Quebec [5]

There exists plenty of environmental assessment methods. Among these methods, LCA is the most commonly used in industry and in the governments environmental strategies. In addition to the holistic investigation of all the pavement life cycle stages (from cradle to grave), LCA results can be implemented in sustainable development decision-making. Although a lot of investigations and practices have been deployed in the pavement system, an LCA assessment tool to properly quantify environmental sustainability in the pavement system is still missing. Identifying the appropriate framework for this assessment is a crucial task and choosing a simplistic framework may mislead decision-makers.

1.2 Dissertation organization

The dissertation is organized in the following manner:

Chapter 1 provides an overview of the context of this work and the organization of this dissertation.

Chapter 2 is divided in two parts. In the first part, a brief introduction on fundamentals of LCA and comparison of ALCA and CLCA frameworks is presented. In the second part, a review of pavement LCA studies incorporating the research gaps and opportunities is dicussed. The latter part of chapter 2 was published as a review paper in Journal of Cleaner Production. Nevertheless, an update was performed on the literature review to include recent studies that have been published since then.

Chapter 3 discusses the problem statement and the objectives of this research project.

Chapter 4 presents the proposed model to treat the uncertainty and variability sources in pavement LCA. The methodology is applied to an ALCA case study and data quality uncertainty, variability of construction materials and methods, and uncertainty due to the methodological choices were propagated to the results.

Chapter 5 presents the development of the novel dynamic CLCA framework, including the procedure of defining the LCI and its connection to dynamic CFs. The method was applied to a case study of pavement selection in Quebec. Then, the model proposed in Chapter 3 was used to integrate the data quality and model uncertainties as well as the variabilities in different life cycle phases.

Chapter 6 provides a summary and an overview of main findings obtained in this research project. In addition, the originality of this dissertation is presented in this chapter. Recommendations for future work are also presented.

CHAPTER 2 LCA CONCEPTS AND CRITICAL REVIEW OF LITERATURE

2.1 An introduction to LCA

Recent environmental policies require a framework for identifying the alternatives in which the investments are the most profitable in order to guarantee a sustainable development. Hence, many societies tend to assess and compare their strategies and products' environmental impacts by performing an environmental assessment of the different present options. Life cycle assessment (LCA) has become an accepted tool for performing these analyses and answering important questions about current topics of concern to the public. In fact, LCA is helping the societies to quantify, classify, and assess the environmental impacts of any interactions between ecosphere and technosphere.

Road transportation is known for its considerable energy and environmental (i.e. emissions) impacts. For example, it is reported that more than 120 million gallons of gasoline and 35 million gallons of other types of fuels are being consumed in the U.S. highways every year [9]. Such considerable amount of fuel consumptions leads consequently to different air, water, and soil pollutions [10]. Apart from the fuel consumption, it was also demonstrated that moving toward sustainable development in pavement construction projects can lead to lowering their Greenhouse Gas (GHG) emissions, and their life cycle cost [11]. Hence, road stakeholders are interested in evaluating environmental burdens by considering different life cycle stages of roads.

Taking into account the importance of road transportation in the people's daily life and being aware of its important role in environmental impacts, an assessment framework for pavement alternatives is of great importance [12]. Hence, methodological improvements helping to assess the environmental burdens associated with the pavement options needs to be developed and implemented accurately.

2.2 Fundamentals of ALCA and CLCA

Life Cycle Assessment (LCA) is a holistic tool that can help a product or service stakeholder to reach the objective of sustainable development of their outcome. Indeed, LCA helps to quantify, analyze, and compare environmental impacts of diverse types of product or service from material extraction (cradle) to their end of life (grave) phase. The LCA procedure starts from drawing a schematic view of life cycle phases of the product system from cradle to grave followed by quantification of the environmental burdens associated with each phase. After that, the quantified elements will be aggregated and classified into lower number of categories to facilitate the decision-making process.

The principles and framework of conducting an LCA studies comprises four phases of any LCA, which are detailed in ISO 14040 and 14044 standards (See Figure 1). Based on the aforementioned standards, LCA methodology is divided into the following steps [13, 14]: 1) goal and scope definition; 2) Inventory collection and analysis; 3) environmental impact assessment, and 4) interpretation of the obtained results. The relationship between the different LCA phases as well as applications of LCA are presented in Figure 2.1.

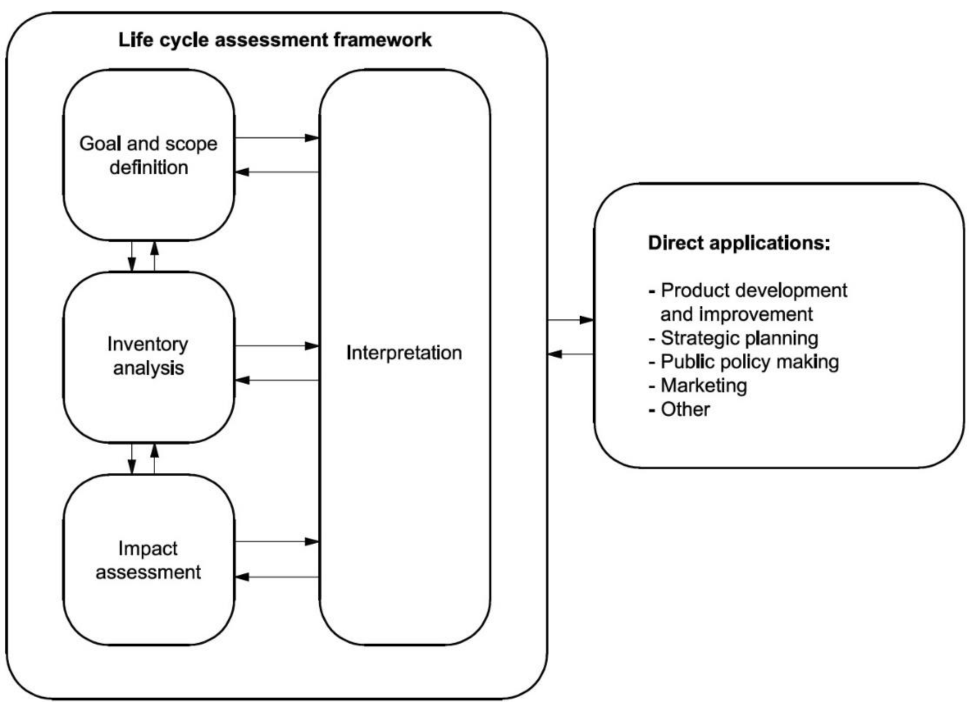

Figure 2.1. Life cycle assessment (LCA) framework adopted from ISO 14040 [13]

Depending on the application and goal of the study, LCA studies can be divided into attributional and consequential frameworks. An attributional LCA (ALCA) is known as the traditional LCA framework that can capture the environmental burdens within the defined system boundary of the life cycle. Environmentally relevant physical flows to and from a life cycle and its subsystems is the main description of ALCA. On the other hand, consequential life cycle assessment (CLCA) describes how physical flows can change as a consequence of an increase or decrease in demand for the studied system [15]. Formerly called change oriented LCA [14] considers the consequences resulting from a given choice and for short or long-term environmental impacts of the decisions. System description and methodological differences between ALCA and CLCA are presented in the context of ISO framework.

2.2.1 Goal and Scope definition

In this step, questions or hypotheses is formulated and objectives and boundary of the studied system are defined. In fact, goal and scope definition respond the following important questions:

- What is the reason of conducting LCA?
- What is going to be analyzed?
- How is it going to be analyzed?

Several goals have been proposed in the ISO 14040 standard [13] and the Environmental Protection Agency (EPA) guide [16] including: product development, public policy making, process optimization, marketing, strategic planning, and decision making.

According to ISO 14040, various parameters shall be specified and clarified at the scope including the product’s functions and functional unit, system boundary, data collection and assumptions, life cycle impact assessment method, data quality requirements, and allocation procedure in case of multifunctional processes or recycling [13].

a) Goal and Scope of ALCA

The ALCA methodology is commonly implemented to find hotspots in a product life cycle, product declaration, and generic consumer information [17]. Energy and material flows along the product's supply chain during use and disposal or recycling at a point in time (typically short-time perspective) are tracked by ALCA. Formerly called “accounting” LCA includes all flows throughout a product chain, regardless of their relevance to a change in the modeled system [18]. Figure 2.2 presents a schematic view of a system boundary and its interaction with the ecosphere with an ALCA framework. In the context of ALCA, only attributes to the direct and indirect emissions corresponding to the reference flows and background unit processes are investigated. Lack of future investigation and ignoring the market condition, such as capacity, policy, and competitiveness of product system, leads to a decision in the ILCD handbook that they recommend implementing the ALCA only in contexts where no decision is to be made based on the study results [11].

Depending upon the goal of the ALCA, function of the system is defined by description of the service performance of the investigated system. Functional unit is simply determined as a quantitative form of the function. Due to the inconvertible unit processes in the system boundary and also considering the use of average data, there is always a linear relationship between functional unit size and the calculated environmental impacts in ALCA [19]. For example, in case of electricity production, life cycle inventory results demonstrate the average electricity production in a specific spatial and temporal context. The results could be presented as the emissions per kWh generated electricity. The magnitude of the functional unit (kWh) does not affect the conclusions because the average emissions and consumptions of the electricity system scale linearly with the functional unit.

Allocation in ALCA is commonly followed by the ISO standard recommendations. It can be started from subdivision or system expansion in the system boundary and flowed by physical relationship, and non-physical (economic, mass, and etc.) relationship between co-products, respectively [14]. In fact, the choice of allocation method in ALCA manifest a source of uncertainty in the framework that should be categorized in the uncertainty due to the methodological choices. It was reported that the allocation choices can affect the preferred scenario when comparing different alternatives of pavements and therefore should be carefully treated in the ALCA studies.

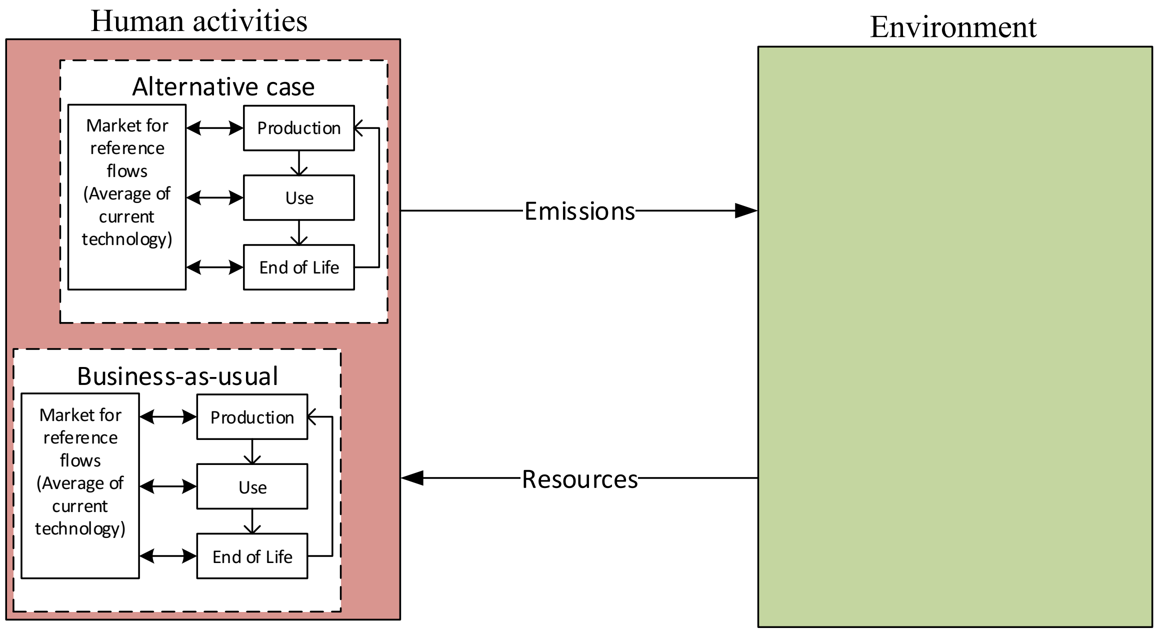

Figure 2.2. Schematic presentation of ALCA framework

b) Goal and Scope of CLCA

Based on the definition of Shonan guidance principles[a] [20], CLCA is "a system modelling framework in which activities in a product system are linked so that activities are included in the product system to the extent that they are expected to change as a consequence of a change in demand for the functional unit". Indeed, it seeks the environmental consequences (in short and long term) of possible (future) changes between alternative product systems. The goal of a CLCA study can discuss the following question: "How would world markets be affected by a change in a product or service and what would be the consequences on the environment?" Therefore, there is always a comparative nature and an investigation of specific suppliers to the demands in CLCA goal, which distinctively seeks the consequences of the substitution in the world. At the application level, the CLCA framework helps evaluating the environmental consequences of a decision that are dependent on many factors including the economic, technological and environmental mechanisms.

Searching in the literature of CLCA, it was observed that Ekvall seems to be the first to propose the inclusion of the indirect impacts in the life cycle assessment methodology [21]. This

[a] Global Guidance Principles for Life Cycle Assessment Databases

inclusion would allow the interpretation of the environmental consequences induced by the market and that take place outside the supply chain. Among the first economic techniques linked to the CLCA methodology, there is the partial equilibrium model, in a simplified application. The assessment of consequences at this level is suitable for the case of mature technologies [22]. However, as a simplification, the step-wise procedure proposed by Weidema has been implemented in many CLCA studies [23]. Figure 2.3 presents the methodology of a CLCA study. The main difference compared to Figure 2.2 is that the CLCA system boundary ideally includes the equilibrium of demand and supply of different intermediate flows and recycling markets [24].

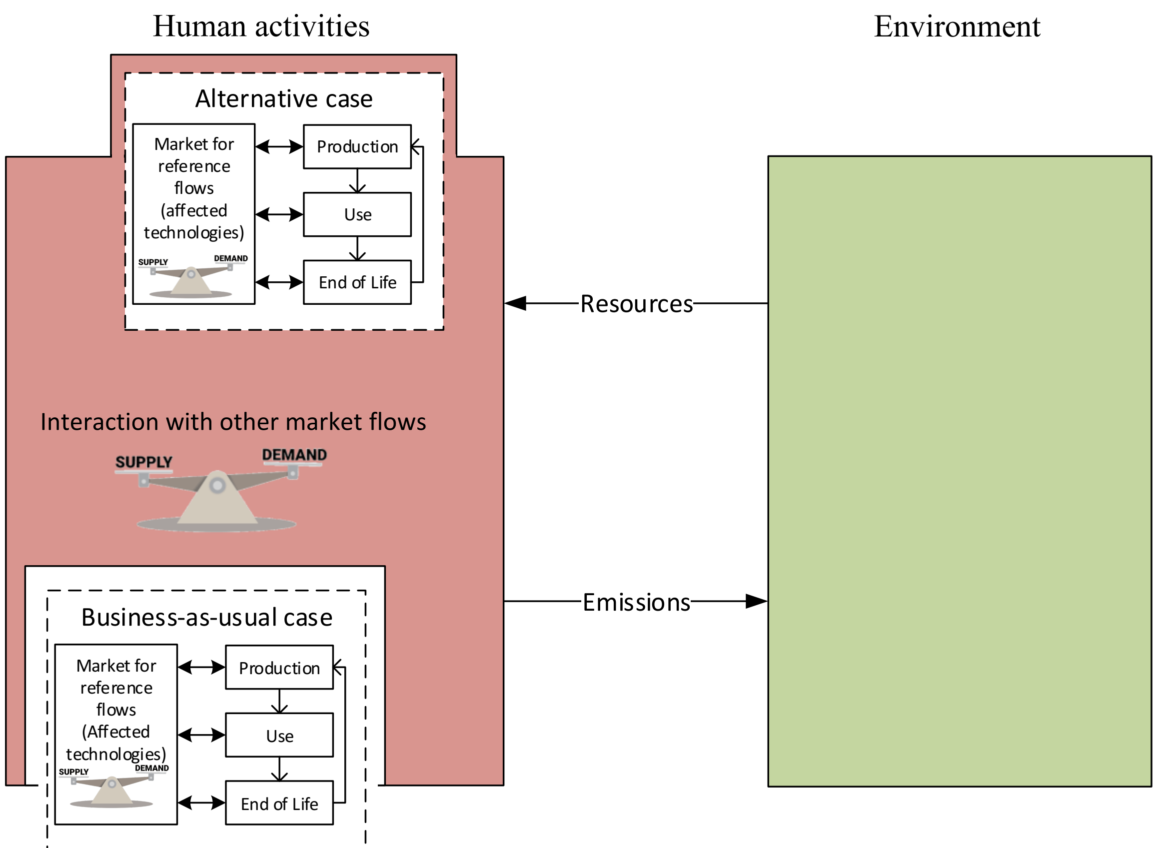

Figure 2.3. Schematic presentation of CLCA framework

Within the context of CLCA, an estimate of the system-wide changes in emissions and consumptions will result from a change in the level of the functional units produced [25]. Therefore, the results depend on the magnitude of the change. The change caused by a small increase or reduction of the product are described by environmental data for the marginal technologies (affected technologies). Hence, the size of functional unit can explicitly influence on the study results. Functional unit selection in CLCA plays an important role due to the comparative nature of CLCA and the fact that it is the basis of equivalence, when comparing different product alternatives in CLCA studies [26].

In case of CLCA, allocation and recycling are typically solved through system expansion because multifunctional processes and recycling influence certain processes outside the investigated life cycle [15]. In this sense, system expansion is performed to maintain equilibrium of product systems in terms of product outputs, through considering an equivalent production in the other systems.

2.2.2 Inventory analysis

The objective of the inventory analysis is to list all the substances that are emitted into or extracted from the environment during the life cycle of the product or service. The ISO standards [13, 14] for life cycle inventory analysis explain the construction of LCI process chain models by combining data of unit processes. Procedure of compilation on all unit processes' inputs and outputs of the product or service is presented in this step. Quantification of the emissions and resources in addition to description of every unit processes are conducted in detail.

In recent years there is a shift in LCA to larger scale decision contexts. Part of the reason for this shift has been the argument that since LCA is useful for determining the environmental impacts of a product. Ekvall highlighted the importance to distinguish between these frameworks, in order to reduce several methodological problems, especially in the inventory level [27]. Based on this shift, life cycle assessment methods are classified into two main frameworks: attributional and consequential. In the next sections, explicit description of the aforementioned frameworks in life cycle inventory phase will be presented.

i. Life cycle inventory of ALCA

The inventory of an ALCA determines the flows associated with the delivery of the specified functional unit of the system, i.e. reference flows. The ALCA framework includes all the processes that have a significant contribution to the product of concern and to its function [25]. As shown in Figure 2.2, the environmental flows that contributed in impact assessment are located inside the system boundary and there is a direct relationship between the unit processes and the emissions. Indeed, what is really happening in the ALCA system should be reflected by the system boundaries and the type of data used. In the modeling of the system's life cycle, data representing the average performance are usually used in order to attribute the average environmental burdens for producing a unit of the product in the system [14].

ii. Life cycle inventory of CLCA

Unlike ALCA, the CLCA framework considers that a change in demand for a resource in a product life cycle will affect the international markets at the margin. Thus, the initial data quality goal for many of the consequential life cycle inventory subsystems is global marginal data [24]. Moreover, the CLCA framework takes into account unit processes inside and outside of the product's system boundaries [28]. It also applies economic data to measure physical flows of indirectly affected processes. In addition, ALCA normalizes the total impact of a given product system to its corresponding functional unit, while the CLCA inspects both, the marginal and non-marginal effects of the alternatives.

The technology affected by the small changes and capable of dealing with the marginal effect is called affected technology [29]. The recognition of the affected technology is based on a five step procedure proposed in [17] and it is as follows:

1. The time horizon applied (short or long-term)
2. If the change affects only specific processes or the market in general
3. The affected market's trend in the volume
4. The presence of any potential to increase or reduce the production
5. If the technology is least or most preferred

This procedure has been applied to various markets and examples are given in different disciplines [30-33]. However, the use of the five-step method for determining the market trends highlighted the different types of constraints to which the technology in the market of concern can be subjected. These limitations vary between political, technological, physical and economical [17].

iii. Temporal aspect of CLCA and ALCA frameworks

The methodology of conducting LCA, whether it is attributional or consequential, can be assessed in short or long-term perspective. Generally, in the context of short-term, the existing technologies are investigated in the life cycle inventory. While in long-term, future market will be assessed and employed to generate corresponding life cycle inventory. Each temporal aspect of the LCA methodology can be considered in three ways. The values corresponding the LCI can be taken in to account as a constant (Fixed) value in time and therefore all the possible changes in time may not be acknowledged. While in certain cases, the inventory values are changing in time. If the changes over time follow a regular pattern (i.e. an equation can be developed), it can be called a dynamic inventory.

2.2.3 Life cycle impact assessment (LCIA)

Three elements can be included in this step of the LCIA and they are classification, characterization and weighting. The impact categories are selected, and the emissions are classified under the corresponding classes. All the unit processes listed in the inventory analysis are converted into environmental impacts corresponding to several impact categories based on "cause and effect" chains. The inventory results are directly assigned to the corresponding midpoint and endpoint categories through characterization factors. Since the conversion of life cycle inventory is not involved with the type of data (marginal or average) and the goal and scope of the study, there is no change in CLCA and ALCA methodology to conduct this stage.

2.2.4 Interpretation

Interpretation of the results of the three previous phases responses to the stated objectives in the first step. In addition, iterative characteristic of the LCA lets practitioners to reconsider what was missed out in the interpretation step. Whether it is ALCA or CLCA, a conclusion forms depending on the application and the goal and scope of the study. In comparative studies, the most common interpretation is the relative mitigation of an alternative in form of normalized quantity [15]. Plevin et al. [19] stated presentations of LCA results in the attributional framework usually do not acknowledge the constraints in the world and therefore it might mislead practitioners who use the study results for a decision-making. On the other hand, CLCA can draw a conclusion on indicating that the difference reflects consequences, rather than only an accounting of process emissions.

In terms of uncertainty analysis, it was stated that due to stoichiometric relationship between inputs and outputs of ALCA, there is a low level of uncertainty in such framework [34]. It was also reported that the ALCA framework is nearly always highly uncertain because it does not take into account a representation of complex socio-economic systems in decision-making contexts [35]. The future is inherently uncertain and this uncertainty sets a limit to all attempts to describe future consequences of a change [36-38]. However, Widema et al. [17] claimed that uncertainty in ALCA is inherently existed due to unknowable and uncontrollable estimations when considering a prospective context. Another study by Weidema et al. proposed a data collection method in which the level of uncertainty can be decreased by the uncertainty involved in forecasting market data [35].

2.2.5 Summary of CLCA and ALCA frameworks

Considering the proposed framework by ISO series, the main differences between the ALCA and CLCA are in the goal and scope definition, life cycle inventory, and interpretation phases. When it comes to their application in decision-making, the ALCA is to be improved on the level of relevance related to the situation being studied, while the CLCA framework is to be developed to include consequences of the change in the system. In terms of inventory, marginal data and identification of affected suppliers are mandatory in CLCA while data collection in ALCA is based on the average data. There is no difference in the LCIA stage of ALCA and CLCA while the conclusions made from each framework may be distinctive due to the different goals defined for each framework. A summary of the difference between ALCA and CLCA is presented in Table 2.1.

Table 2.1. Differences in conducting an LCA study in attributional and consequential frameworks

Life cycle stage	**ALCA**	**CLCA**
Goal of the study	Understanding the emissions and consumptions directly associated with the life cycle of a product, hotspot finding, and environmental product deceleration	Informing policy-makers and consumers on the changes in total emissions and consumptions from a purchasing or policy decision.
System boundary	The processes and material flows directly used in the production	All processes and material flows which are directly or indirectly affected by a change in the output of the product
Type of inventory data	Average	Marginal
Allocation methods	Allocation rule is based on the ISO recommendation: Subdivision or system expansion, physical relationship, non-physical relationship	System expansion
Distinct uncertainty sources	Uncertain in terms of many methodological choices and in case of decision-making	Uncertain due to the availability of market data and interactions in the world

2.3 Life cycle assessment of pavements

This section is an updated version of the recent critical literature review on LCA of pavements, which is published as a review article in Journal of Cleaner Production and is attached to this dissertation as Appendix A.

Many research activities on environmental LCA of pavements have been conducted. From the late 1990's, published studies focused on different phases of pavement life cycle, including asphalt and concrete pavements. The significant variation between the studies is mainly based on available data and different Goal and scope definitions. The critical literature review conducted by Santero et al. provided an exhaustive summary of application of LCA on pavement until 2011. They presented recommendations and necessary actions that should be taken to fill the identified research gaps with respect to construction, use and end of life (EOL) phases of pavement life cycle [39, 40]. As can be observed in Figure 2.4, since 2010, there is a continuous increase of published articles on LCA of pavements. This reflects the increased attention of using LCA in assessing the environmental burdens of pavements. Most of these papers focused on the implementation of innovative technologies on pavements construction, the use of recycled materials [41, 42], and the investigation of various phases of the pavement life cycle rather than improving the applicability and the adequacy of LCA methodology to the pavement problems. In the following sections, a critical literature review of pavement studies based on the ISO framework are presented.

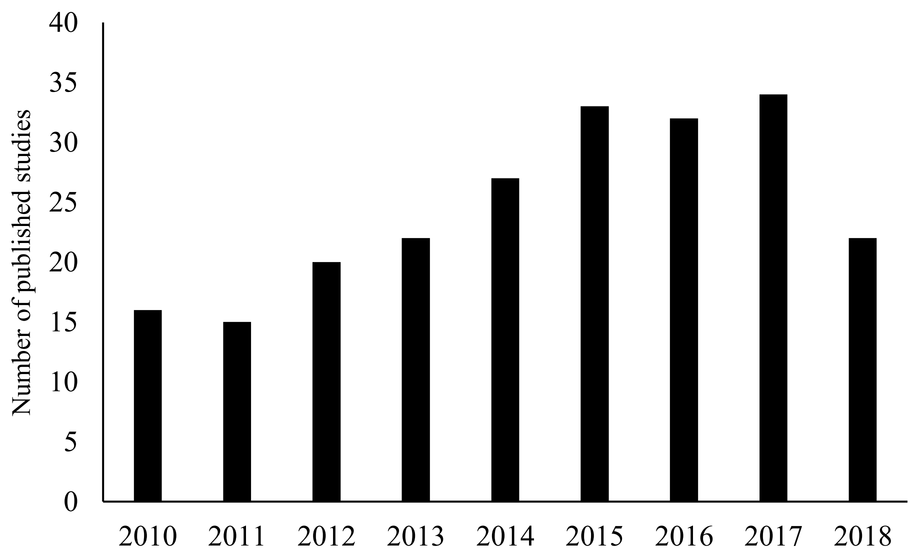

Figure 2.4. Number of research articles and review papers on pavement LCA since 2010. (Search on Scopus Web site on key word “life cycle assessment” AND “pavement”, available by April 2018 [43]).

2.3.1 Goal and Scope Definition of pavements

During the goal and scope definitions, the aim of LCA, its intended audience and its application shall be highlighted. In addition, the scope of the study shall be defined according to the ISO series. The latter includes definition of the function of the pavement, functional unit (FU), reference flows, and the system boundary. When two or more product systems are compared, FU and system boundary definition play a key role in the LCA results [26].

Table 2.2 shows the goal and scope definition elements presented in the reviewed papers. It is worth noting that the major cited papers in Table 2.2 and the reviewed ones, comparing different type of pavements, shows a significant heterogeneity of functional units and other components. LCA standards such as ISO 14040 and 14044 have no technical details on, for example, phases and processes that should be included in the assessment, life spans that should be analyzed, or what are the minimum data that should be considered in the LCA modeling. Beyond the inconsistencies between the publications, the significant differences in calculated life cycle environmental impact results make their comparison simply impossible. The variations of different sections of goal and scope definition, and consequently on LCA results are explained in more details in the sub-sections.

Table 2.2. Goal and scope variations as function of the assessed region

Region	Ref	Functional unit (FU)	Type and number of pavement			Analyzed period (years)
			Concrete	Asphalt	Other	
North America						
Colorado	[44]	1-km lane	2	1	-	40
Illinois	[45]	1-mile lane	-	4	-	45
Missouri	[46]	Not mentioned	1	1	-	50
Michigan	[47, 48]	10 km of a 4-lane road	1	1	1*	40
California	[49]	4 different FUs**	2	2	-	5 (asphalt); 10 (concrete)
Virginia	[50]	5.89 km long, 2-lane of Interstate	-	1	-	50
USA	[51]	1 km of a two-lane road	2	1	-	40
Texas	[41]	4.8 km of 2 and 3-lane road	5	-	-	20 (JPCP), 30 (CRCP)
Europe						
Italy	[52]	1 km of a two-lane road	-	9	-	30
Portugal	[50]	1 km of 6 two lanes road	-	6	-	40
Spain	[53]	1 km of a two lanes road	-	4	-	40
UK	[54]	200-m and 520-m of dual and single carriageway	-	1	-	20
Rest of the world	[55]	1 km of a two-lane road	-	4	-	20
China	[56]	one-mile runway for carrying aircraft	-	6	-	40
Hong Kong	[57]	1 km of road	-	3	-	40
Total			13	44	1	-

(*) refers to engineered cementitious composite

(**) Two of the FUs include 10 miles length of two lanes road with 34000 and 86000 annual average daily traffic with 35 and 25% truck traffic, respectively. The other FUs consist of 5 miles length of two and four lanes roads and supporting 3200 and 11000 annual average daily traffic, which include 15 and 29% truck traffic, respectively

i. Functional Unit

ISO 14040 defines FU as "quantified performance of a product system for use as a reference unit" [13]. As mentioned earlier, when two or more product systems are compared by using LCA, functional unit plays a key role in the LCA results [26]. Dale and Kim reported that selecting different FUs may result in different outputs and conclusions for the same study [58]. In pavement LCAs, FU should consider the definition of physical properties of the pavement system, including design, structural components, and material properties. FU must also reflect effective exterior factors on the pavement, such as traffic load. In a comparative study of pavement LCA, FU acts as a reference unit to which all inputs (material resources and energy) and outputs (emissions to air, water, and soil) are normalized.

Santero et al. mentioned that variation of FUs in pavement LCA studies makes it impossible to compare the results [39], and to assess their variations following different FU. Similar to pavement LCA, this observation is reported in LCA's dealing with different in other product systems [26]. In order to make LCA conclusions more robust, it will be interesting to systematically implement different FUs, as a sensitivity analysis, as done by Loijos et al. [59] and Chen et al. [60], who implemented 12 different FUs to analyze 12 types of concrete pavements. The same approach was also followed by Wang et al. [49] and Santos et al. [50]. When we refer to Table 2.2, the most frequent FU is 1 km or mile of a road with a specific number of lanes. However, it cannot be totally appropriate to reflect road functions if the roadway classification (interstate, urban, rural, and pedestrian) and its lane width in addition to the number of lanes are not taken into account. By adding these characteristics, we implicitly reflect the approximate average daily traffic within the FU. Also, this makes it easier for LCA practitioners to take the advantage of available case studies and apply them for their own cases.

ii. System boundaries

Referring to ISO 14040, system boundary definition involves the selection of activities and processes included within the life cycle phases of the pavement [13]. It also involves taking into account the appropriate geographical and temporal scope such as the location and the period of the assessment. Different types of decisions are outlined based on at what level of complexity (network or specific project) and at what stage within the planning process (early planning or late planning/design) the decision is to be made [61]. Such decisions influence system boundaries selection by using attributional or consequential LCA. Selecting an inappropriate system boundary that does not reflect the assessed pavement reality may lower the degree of LCA practitioner's confidence in decision making [26].

As shown in Table 2.3, there is a significant variation in selected pavement's life spans, which ranges from 5 to 50 years. In some publications, they have chosen recommended life span by local transportation administration or based on rehabilitation program and life design of the road [62]. This comes in contrast to other studies where the reason of choosing the selected life span is simply not mentioned [50, 53].

Assessing the pavement system over a time horizon puts forward a major challenge. Some approaches were proposed for determining the analysis period. For example, using 1.2 to 1.5 times the longest functional design life among all alternatives is a commonly used approach when conducting a life cycle cost [10]. Consequently, the defined life span will be long enough in order to include influential factors in the use phase, like traffic growth rate. Such consideration is rarely checked in the reviewed papers. A sensitivity analysis by Reza et al. showed that expanding life span up to 70 years could substantially increase direct and indirect energy consumption by 40% in operation and maintenance phase of the pavement LCA [62].

In addition to the pavement's life span, the system boundary should also encompass the following phases: material production, pavement construction, use, maintenance and repair (M&R), and EOL. Most of the reviewed papers focused on raw materials extraction, their transportation (including equipment), construction, and maintenance and repair (M&R). However, in some studies, transportation needed during each phase (e.g. transportation after raw materials production) of the life cycle was assigned to that phase [63, 64]. In contrast, other studies have considered all the transportations during life cycle as a stand-alone phase in the life cycle [50, 65, 66]. The M&R is also a good example of non-uniformity in pavements LCA. In some cases, M&R and construction is presented as a separate phase [50], where in others, M&R

is defined as a stand-alone phase [45, 67]. The EOL and use phases were frequently not considered, because of the cut-off approach[b] (in the case of EOL) [53].

Since 2011, studies are increasing their focus on the use phase, by considering, for example, fuel consumption and emissions as a consequence of surface roughness and traffic delay (See Table 2.3). However, they are not the only parameters to consider during the use phase. As an example, albedo effects, lighting, noise, and leachate can substantially affect the environmental impacts of the pavements, and until now, there is rare comprehensive studies incorporating all these components of the use phase.

[b]"*The cut-off system model in short, is based on the Recycled Content, or Cut-off, approach. The underlying philosophy of this approach is that primary (first) production of materials is always allocated to the primary user of a material. If a material is recycled, the primary producer does not receive any credit for the provision of any recyclable materials. As a consequence, recyclable materials are available burden-free to recycling processes, and secondary (recycled) materials bear only the impacts of the recycling processes. For example, recycled paper only bears the impacts of waste paper collection and the recycling process of turning waste paper into recycled paper*" [68] US EIA. U.S. Energy Information Administration, Petroleum Supply Annual, Volume 1 2005-2011, 2013.

Table 2.3. Main used databases in pavement LCAs

Region	Ref	Studied process in additional car fuel consumption	Selected database
North America			
Colorado	[44]	Traffic delay, roughness	Concrete production and End of life: Reiner,2007 [69] Bitumen: Eurobitume,2011 [70] Onsite equipment: Zapata and Gambatese,2005 [71]
Illinois	[45]	-	Pre-production: Monitoring resource consumption: US EIA[1], 2013 [68] Construction: Input –Output database, 2013 [72]
Missouri	[46]	Traffic delay, Rigidity and Roughness, Albedo, Lighting	Cement: PCA[3],2011 [73] Construction processes: International Grooving and Grinding Association, 2009 [74]; Stripple, 2001 [75] Generic data: ecoinvent V. 2.2, 2010 [76] and USLCI[2],2012 [77]
Michigan	[47, 48]	Roughness	PCA, 2002 [78] Keoleian et al., 2005 [79] A database from SimaPro 6.0 (The used database is not mentioned)
California	[49]	Roughness	Stripple, 1998 [75] ATHENA, 2006 [80] Ecoinvent V. 2.2, 2011 [81] USLCI, 2011 [77] PCA, 2006 [82] Some other unmentioned sources
Virginia	[50]	Roughness	Aggregates: Stripple, 2001 [83] Asphalt: Eurobitume, 2011 [70] Cement: PCA, 2006 [82] All energies except electricity: GREET, 2013 [84] Electricity: US EIA, 2012 [85]
USA	[51]	Traffic delay and roughness	Materials module: PCA, 2007 [86]; Stripple, 2001 [83] Steel production: GREET V 2.7 [87]
Texas	[41]	Roughness	All the phases: EIO-LCA database[72]

Region	Ref	Studied process in additional car fuel consumption	Selected database
Europe			
Italy	[52]	-	PaLATE database, 2006 [88] Transportation: Mauro, 2015 [89]
Portugal	[50]	Traffic delay and Roughness	Bitumen and Bituminous emulsion: Eurobitume, 2011 [70] Aggregates: Jullien et al., 2012 [90] Tap water: Ecoinvent V. 2.0, 2007 [91] HMA production: US EPA[4], 2004 [92] Transportation of materials, Construction equipment operation, On-road vehicles operation: EEA[5], 2013 [93] Electricity: Dones et al., 2007 [94] Crude oil: DG, 2008 [95]
Spain	[53]	Traffic delay	Raw materials and products, electricity, fuels, disposal: EcoinventV. 1, 2003 [96] Synthetic Zeolite: Fawer, 1998 [97] machinery, Fuel consumption and air emissions from the paving machines and Transportation: EEA, 2009 [98]
UK	[54]	Traffic delay, Surface roughness, texture depth	Construction materials and equipment: [99] Traffic delay emission: [100] Fuel consumption: [101]
Rest of the world	[55]	Roughness	Consumption and emission related to Rolling resistance: Laboratory experimental Others phase consumption and emission: not mentioned
China	[56]	-	Asphalt binder: [102] Aggregates: [86] Polymer additive: [70] Asphalt production: ecoinvent v.2.2 [91] Construction equipment and Transportation: [103]
Hong Kong	[57]	Roughness, Traffic delay	Asphalt binder and aggregates: [80] Limestone filler: [47] Construction equipment: [104] Fuel consumption: [105]

[1]U.S. Energy Information Administration, Department of Energy
[2] U.S. Life Cycle Inventory
[3] Portland Cement Association
[4]U.S. Environmental Protection Agency
[5] EMEP/EEA air pollutant emission inventory guidebook

2.3.2 Inventory analysis of pavements

Referring to ISO 14044, the second LCA step to conduct after the GOAL AND SCOPE definition is life cycle inventory (LCI) analysis [14]. The inventory analysis covers all collected data (and their validation) that represent life cycle phases within the defined system boundaries. Challenges with data (inventory) types, their collections and their integration in pavement LCA is discussed in the following sub-sections.

Inventory analysis of pavements is mainly subjected to difficulty during material, emissions and energy flow collection for processes modeling. LCAs are conducted by using different databases [106], such as ecoinvent[c], GaBi[d], or ELCD[e], etc. Based on Table 2.3, a significant number of databases are being used in pavement LCAs. Wang et al. conducted a study comparing the environmental burden of a pavement base by using four different databases [49]. They showed that as a result of using various databases, the environmental burden variations increase by 25%. Using localized and updated database seems, therefore, to be necessary. However, beyond these two necessary criteria, different data are still missing, and their inclusion is necessary to increase the robustness of the results. In addition, using various databases in a single case may avoid analyst to check the consistency or the completeness of the background processes in the product system. The following subsections present in more details the missing data to be included in future life cycle inventory (LCI) databases.

i. Pavement surface roughness

Effect of pavement surface on fuel engines consumption and emissions was recently discussed in numerous papers. Taylor and Patten showed that Portland cement concrete and composite could substantially decrease the amount of fuel engines consumption in comparison to hot mixed asphalt (HMA) [107]. In contrast, European Asphalt Pavement Association clarified that fuel consumption is less influenced by type of pavement rather than general state and road user type [108]. Akbarian et al. presented a model drawing a relationship between pavement deflection

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[c] www.ecoinvent.org

[d] http://www.gabi-software.com/international/databases/gabi-databases/

[e] http://eplca.jrc.ec.europa.eu/ELCD3/

and car fuel consumption [109]. As shown in Table 2.2, surface roughness is one of the most significant parameters in pavement LCA. Studies have shown that up to 2% reduction in car fuel consumption can be achieved by 10% reduction in rolling resistance induced by surface roughness [12, 110]. Majority of research in the field of pavement LCA considered the surface roughness based on international roughness index (IRI). The IRI is the ratio of a standard vehicle's suspension motion divided by vehicle distance traveled during the measurement [111].

Louhghalam et al. mentioned that as the car speed and temperature increased, significant difference between fuel consumption on various types of pavement was observed [112]. Based on their research, the car fuel consumption of the vehicles on asphalt pavement can be doubled at ambient temperature of 30°C compared to the consumption at 10°C. In addition, they showed that considering car speed reduction from 80 to 20 km/h, the fuel consumption on asphalt pavement can increase from 3.5 to 8.1 L/100 km. Portland cement concrete pavement was not sensitive to the aforementioned criteria. As a result, a revision in consideration of car fuel consumption emission based on local condition and car speed seems to be necessary. The car fuel consumption in asphalt pavement LCA needs to be discussed as a temporal criterion particularly in region with significant daily, monthly and seasonal temperature. The variation of traffic in travel lanes are also important to consider since the rate of surface deterioration is changing as a function of traffic load. For example, the outer lanes usually comprised a significant volume of trucks and therefore the surface roughness may increase severely compared to the one in inner lane. Hence, a dynamic assessment and estimation of IRI values for each lane can improve the accuracy of the results.

Tire wears and damage to freight and vehicles due to pavement deterioration need to be assessed in pavement LCA. Theoretical models and empirical investigations have reported strong effects of road surface condition on vehicle repair and maintenance needs, tire wear, and lubrication [113, 114]. As a result of pavement aging, a specific damage is included to the vehicles. Steyn et al. have shown that the amount of GHG emission which is induced in 20 mph speed of vehicle can be duplicated as an increase of IRI from 64 to 512 in/mile [115]. It was also reported that different types of tires can induce a change in car fuel consumption. For example, Kang et al. [116] analyzed that wide-base tires can improve the vehicle fuel economy by 1.5% per axle compared to a conventional tire. The changes in tire-induced consumption should be captured in the environmental impact assessment to enhance the accuracy of IRI- induced fuel consumptions.

ii. Noise

The noise generated by traffic is the main source of noise pollution, which threatens human health. In pavement LCA, the noise is generated in different phases that are directly related to the pavement life cycle; from raw materials extraction to the EOL. As a matter of fact, the noise generated by tires and pavement interaction (for various types of pavement) is also a matter of concerns. This integration of noise generation opens rooms for integration of the noise category and providing a link to human health damage. Several research works have been conducted on tires and road interactions. Petterson et al. demonstrated that stone mastic asphalt can reduce the noise generated by vehicle traffic rather than dense graded asphalt [117]. Another study on pavement materials compared the noise generated by vehicles crossing cobblestones, dense graded asphalt, and open asphalt rubber pavements [118]. Comparing the annoyance level, they clarified that the noise, which has been recorded by tire and cobblestone pavement interaction, is the severest compared to the others. There are also some studies considering porous asphalt and dense asphalt surfaces in term of noise generation [119, 120].

However, noise data are not included in different LCA databases (such as ecoinvent [121]). In addition, the impact of noise annoyance will likely become smaller as less noise generating technologies are expected to be adopted. Therefore, it will be helpful to investigate the potential trade-off between the avoided direct impact due to noise reduction and the life cycle environmental impacts of the developed pavement reducing that noise. Such assessment is still surprisingly absent in the literature.

iii. Lighting

Lighting energy is one of the criteria that are considered in the use phase of the pavement life cycle. Importance of lighting was investigated in some papers. Unanimously, it was demonstrated that vehicles light on asphalt pavements require 50% more lighting power than those on concrete pavement to have adequate illumination for driving [122, 123]. It was also investigated that using recycled materials such as glass in asphalt can lead to greater reflectance compared to conventional asphalt [124]. This phenomenon could be an environmental advantage of using recycled materials that must be taken into account in recycled pavement LCA. A study showed that asphalt pavement uses 720 MWh of electricity more than concrete per kilometer of the road during a 50 year life span [125]. It was also mentioned that once the contrast of surface is changing and hence, surface's retroreflection could vary significantly. The retroreflection of asphalt is increased from 24 to 32 mcd/lx/m^2[f] during a certain number of years. While in concrete pavement, it is decreased from 38 to 31 mcd/lx/m^2.

Generally, the reflection of asphalt and concrete after aging will be increased and decreased, respectively. Even after a while, they could have the same reflection [126].As shown in Table 2.2, effect of surface roughness on car fuel consumption and emissions was measured and implemented in pavement LCA as a direct effect while, surface roughness could indirectly affect the energy consumption through the reflection of light. Taking lighting energy consumption into consideration not only helps to see the effect of surface roughness, but also can illustrate the importance of maintenance strategy of the pavement. These temporal variations in the reflection of light as a consequence to different type of pavements open up opportunities to incorporate temporal behavior in LCA.

iv. Albedo effect

Solar reflectivity of pavements (known as albedo[g]) is an effective property of the pavement connected with climate change impact category. Higher albedo leads to a decrease in heat island effect [40]. The surface albedo can also exert a radiative forcing by perturbing the shortwave radiation budget. Generally, the radiative forcing due to surface albedo increases is weaker when

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[f] mcd/lx/m2define the unit millicandelas per lux per square meter

[g] Methods of calculation of albedo and more precisely the pavements type effects on solar reflectance are still in debate. Although some researchers clarified that Portland cement concrete has less urban heat island effect compared to asphalt, recent ideas decline the hypothesis based on new albedo measurement methodology [127] M. Swanson, A. Hobbs, Urban heat island effect: Comparing thermal and radiation effects of asphalt and concrete pavements on adjacent buildings using CFD methods, Contact Urticaria Syndrome, (2014) 33.. As a result, further research is needed to clarify the phenomenon.

clouds are included as less solar radiation is available to be reflected at the surface [128]. A study showed that increasing RF induced by an increase of 1% in solar reflectance, resulted to a reduction of 2.55 kg and 1.27 W/m^2 of CO_2 and RF, respectively by each square meter of pavement [129]. These estimates do not take into account the albedo as a function of time [130, 131]. The GWP of RF, which is induced by the albedo effect, can have different impact in time due to the time-dependent change in the denominator of the GWP calculation, i.e., the RF of CO_2. Therefore, a detailed temporal estimation of RF induced GWP can possibly improve the accuracy of the results. Some studies introduced time dependent parameters in their estimation of the amount of produced CO_2 [132, 133]. Eq. 2.1 shows the equation for calculation of estimated CO_2 (in metric tonne) based on RF [83]:

$$CO_2(t) = \frac{A \times RF \times \ln 2 \times P_{CO_2} \times M_{CO_2} \times m_{air}}{A_{earth} \times \Delta F_{2x} \times M_{air} \times AF(t)} \qquad (2.1)$$

where A is the albedo effective surface area (m^2); RF is the value of radiative forcing at the top of the atmosphere (W/m^2); P_{CO_2} is CO_2 partial pressure; M_{CO_2} is the molecular weight of CO_2; m_{air} is the total mass of atmosphere; A_{earth} is the surface area of Earth; ΔF_{2x} is the RF due to the doubling concentration of CO_2; M_{air} is the molecular weight of dry air; and AF(t)is a time dependent variable calculated using Eq. 2.2.

$$AF(t) = \frac{\int_0^t (0.217 + 0.259e^{-\frac{t}{172.9}} + 0.338e^{-\frac{t}{18.51}} + 0.186e^{-\frac{t}{1.186}})}{t} \qquad (2.2)$$

Where t is life span (year).

Yu and Lu developed a model which is not only able to estimate a time dependent CO_2, but also made it possible to calculate in both deterministic and probabilistic way [134]. Akbari et al. recently reported that albedo is highly affected by aging [135]. Implementing different scenarios and strategies on pavement maintenance would highly influence on albedo during pavement life cycle. Calculating albedo with respect to M&R strategies should be explored in future pavement LCA. In addition, new technologies affecting long-term albedo effects are going to be developed, such as photocatalytic surfacing and pavements colored with infrared reflective cool paints [136, 137]. Environmental impacts of implementing these upcoming technologies have not been yet considered in pavement LCA. A baseline of a fully reflective surface was considered when calculating the RF effect of the pavement, meaning that the relative difference between pavement and a surface with albedo value of 1 is applied to the calculation.

v. Carbonation

One of the phenomena, which are inherently occurred in concrete life cycle, is carbon uptake or carbonation. Concrete carbonation is a process where atmospheric carbon dioxide reacts with calcium hydroxide (portlandite, $Ca(OH)_2$) of hydrated cement to form calcite. The Fick's first law of diffusion and the study by Lagerblad [120] (Eq. 2.3) was adopted to quantify the carbonation in concrete. Many authors used Eq. 2.3 to estimate CO_2 capture (kg/m^3 concrete).

$$\mathrm{CO_2} = \mathrm{k} \times \sqrt{\mathrm{t}} \times \mathrm{c} \times \mathrm{CaO} \times \mathrm{r} \times \mathrm{A} \times \mathrm{M} \qquad (2.3)$$

Where k is carbonation rate coefficient ($mm/\sqrt{year}$), which was calculated as function of concrete properties, t is service life (year), c is the quantity of Portland cement (kg/m^3 concrete), CaO is the amount of CaO in Portland cement (%), r is the proportion of calcium oxide that can be carbonated, A is the exposed surface area of concrete (m^2/kg), and M is the chemical molar fraction of CO_2/CaO. Carbonation rate coefficient for different concrete compressive strength and exposure conditions is widely varied from 0.5 $mm/\sqrt{year}$ (compressive strength higher than 35 MPa and wet exposure condition) to 15 $mm/\sqrt{year}$ (less than 15 MPa and indoor exposure condition).

Previous studies have shown the influence of multiple parameters on concrete carbonation. For example, water to binder ratio plays an important role [138, 139]. Muntean and Böhm stated that carbonation is strongly dependent on the degree of porosity, which is a path for transporting water and CO_2 into concrete [140]. Once the concrete pavement life span is defined, CO_2 capture can be investigated during the service life. A recent study have shown that the CO_2 uptake during the service life of the structure (building) and recycling of demolished concrete is near 5.5–5.7%

by the total CO_2 emission in the building life cycle carbonation and 10–12%, respectively [141]. Based on their model, other parameters such as mixture design, ambient temperature, and relative humidity have contribution in calculating depth of carbonation.

According to García-Segura et al. replacing 80% of cement clinker by blast furnace slag reduced CO_2 capture by 20 % compared to ordinary Portland cement [16]. Another study by Rossick on concrete pavement LCA have shown that 5 to 30% of the produced CO_2 during concrete production can be absorbed by the concrete pavement during use and EOL phase in 9 different scenarios [142].

However, it is important to mention that all the assessments do not encompass the trade-off with other life cycle stages and environmental impacts categories (beyond CO_2 emissions). The CO_2 concentration seems to be another crucial parameter in measuring the amount of CO_2 absorbed by concrete. According to Tam et al. [143], small CO_2 concentrations are associated with rural area where CO_2 content is about 0.03% by total gases in the atmosphere. It was stated that CO_2 concentration would be about 0.3% in metropolitan areas. Conciatori et al. refer to the following CO_2 concentrations 0.015% in land, 0.036% in downtown, and 0.045% in industrial area [144]. Regarding the significant compensation of the emitted CO_2 by concrete production, it seems necessary to include CO_2 absorption of the pavement during use and EOL phases when calculating its environmental burden. This can bring up methodological challenges for future pavements LCA.

vi. Earthworks

One of the activities in work breakdown structure of a road construction, which includes high volume of materials, is earthwork operations. Considerable volume of land must be excavated, filled, and transported for each kilometer of the constructed road. Studies in this field are focused on optimization of cost and energy consumption in the earthworks volume and its transport [145]. It is worthy to mention rigidity of pavement is a key parameter on thickness of sub-layers and consequently the volume of earthwork. Results of a research on different scenarios of embankment and cut sections, including lime stabilization, use of recycling materials, and crushed virgin materials, have shown that there is up to 50% variation in CO_2 emission induced by the implemented scenarios [146].

Although there are many on-going studies on earthwork operation of construction phase, most of LCA studies have not taken it into consideration when comparing different alternatives. The significance of the earthwork in cold regions is reported by Magnusson et al. as filling of excavated soil and rock is in the range of 0.4 to 5.5 tons per capita and year. The use of quarry materials ranged from 4.6 to 8.0 tons per capita and year [147]. One of the reasons neglecting the earthwork refers to specific conditions of a particular project [148]. Therefore, sensitivity analysis considering different scenarios of earthwork is worth to explore in future pavement LCA. As potential scenarios, the amount of excavated earth for road leveling could be a source of materials needed in the embankment sections, or it could supply the aggregates in non-graded concrete. Referring to the study done by Magnusson et al., reusing excavated earth can potentially save up to 14 kg CO_2 per ton of the earth [147].

vii. Dynamic life cycle inventory

It was stated that the lack of temporal consideration of the emissions in the traditional LCA underestimated the amount of emissions and consequently their impact, resulting in a bias of the studies' result [149]. Similarly, a significant variation was observed in the results obtained from the dynamic LCA and the conventional LCA in building sector excluding the temporal changes [150]. Zhang et al. addressed the changes in roughness over time due to deterioration and the related dynamic effects on highway users' fuel consumption and environmental impacts [47]. Similar dynamic approach was proposed by Liu et al. to assess the effect of pavement deterioration on car fuel consumption [44]. Despite of the aforementioned examples, implementation of dynamic life cycle inventory was rarely studied in LCA of pavement. Considering a need for dynamic inventory to assign to dynamic CFs, there is rarely a framework that can be useful for full dynamic assessment through dynamic inventory and dynamic LCIA. Hence, a holistic dynamic life cycle inventory of pavement seems essential to include all the parameters in the inventory assess them as a function of time. Recent studies incorporated the dynamic values of emissions through the time but the scope of the studies did not include the pavement use phase [56, 151].

2.3.3 LCIA and interpretation of pavements

Lack of temporal and dynamic patterns consideration on life cycle impact assessment has often been discussed as a serious constraint of LCA [152]. There are some efforts that was carried out in temporal LCA, in relation with the pavement use phase, such as carbonation, albedo [134] and, pavement roughness [47]. However, very few papers started to integrate the dynamic and temporal aspects in pavement LCA (including for impact categories). A comprehensive research on temporal life cycle impact assessment is needed, especially for systems with a long-life span (such as pavements).

i. Sensitivity analysis

During the interpretation step, sensitivity analysis helps in understanding the impacts of the input data, methodological and hypothesis choices on the LCA results. As an example, a study by Sayagh et al. investigated a sensitivity analysis on allocation scenarios because of its assessment using blast furnace slag (BFS), as a by-product of steel production [153]. Until now, many important parameters in pavement LCA are lacking a sensitivity analysis whereas their influences on the final environmental impacts are not known. The following paragraphs aim to summarize them.

First of all, environmental impacts of supplementary cementitious materials (SCMs) and chemical admixtures in concrete pavements could take an important place in the near future and are still not included in recent concrete LCA [154]. Sensitivity analysis considering blast furnace slag as SCM in concrete has already been conducted [153]. However, there are some other conventional SCMs, such as silica fume and fly ashes, which are produced as by-products and are missing in recent pavement LCAs. Second, Various types of chemical admixtures, such as superplasticizers, shrinkage reducing admixtures, and curing compounds are common in concrete pavement construction. Although the volume of the chemical admixtures in concrete is low (compared to other ingredients e.g. cement, aggregates, and water), the environmental burden associated with their synthesis and toxicological properties is significant [155]. The environmental burdens of the admixtures are still not integrated in common LCI databases such as ELCD, Gabi, USLCI, etc. Comprehensive sensitivity analysis (scenario based) seems to be prerequisite for different chemical admixtures to assess their environmental contribution.

Finally, as it is described earlier in section 2.3.2, the albedo effect can influence the urban heat island, which consequently causes significant variations in the heating and cooling energy demand of vehicles, and decreases the runoff quality. Hence, it could be of interest to integrate pavement temperature and reflectance in a sensitivity analysis. CO_2 uptake also plays an important role due to the carbonation processes. Porosity of the concrete pavement can speed up carbonation. The carbonation rate in rainy weather is low, as the rain relatively blocks concrete pores. Thereby, based on mentioned parameters, carbonation rate will be changed as the humidity and ambient temperature varies [16, 156]. A sensitivity analysis taking into account different carbonation rates is worth exploring.

ii. Uncertainty analysis

During the interpretation step, pavement LCAs should assess the added uncertainty to the results, keeping in mind all the of uncertainty sources: the inventory (quantity and quality) and the characterization factors of the impact methods. For example, implementing Eurobitume LCI database to an asphalt pavement LCA in the U.S. leads to an uncertainty since the information was provided based on the local conditions of European nations, i.e. the geographical correlation. Wang et al. [49] reported that calculated energy consumption in HMA life cycle is changing as a function of selected LCI database, particularly in use phase. It was shown that the variation between the energy consumption in the use phase could be more than 80%. Another source of variation that exists in pavement LCA studies is variability of the flows. Variability stems from inherent changes in the real world, where LCA calculation has not yet been applied to the data (e.g., true differences in production technologies, materials or regions). However, uncertainty is related to converting real-world data to LCA outcomes, where simplification of reality, introduction of subjective choices or lack of precision in estimates of parameters occur and are included in the LCA models [157]. In addition, uncertainty can be reduced with additional measurements, whereas variability inherently exists in the environment and cannot be reduced by additional research [158]. In fact, assessing the combined effects of uncertainty and variability can reflect the robustness of the conclusions. On the other hand, the individual analysis of uncertainty and variability cannot only show where the major variation in the results come from but also help to know how much further we can go to improve the results certainty. So far, no methodology is specified and guidelines and standards, such as ISO 14044, recommend conducting local sensitivity (e.g., one at a time) and uncertainty analyses in comparative studies intended for public disclosure [14].

Summarizing the literature of uncertainty and variability in pavement LCAs, because an interdependent effect of the uncertainty sources exists in the analysis, it is unsound to single them out in the study [159]. Furthermore, the uncertainty of different methodological choices, such as allocation of bitumen and byproducts in pavement construction, has not been included in the probabilistic analysis. When all sources of uncertainties are applied in the analysis, the resulting "absolute" uncertainties often become enormous, making it difficult to draw conclusions in comparative studies [160]. In addition, in comparative studies and particularly in pavement life cycle studies, sources of dispersion are correlated with each other. For example, if an LCA evaluates asphalt and concrete, the uncertainties related to gravel and sand production are assumed to be identical, and only the variability associated with the amount of sand in the mix design of the asphalt or concrete should be considered. Evidence of significant differences in the absolute and relative results are presented by Henriksson et al. [161], showing that absolute uncertainties led to an entirely different conclusion when independent sampling was chosen in each iteration.

2.4 Conclusions and outlook

Due to diverse materials options, different construction methods, distinct maintenance/repair strategy, and their broad lifespan, the diversity of pavement projects gets easily significant. LCA research on various types of pavements increased significantly. Since 2011, the use phase is discussed more extensively: e.g. Traffic delay consequences and surface resistance on excessive car fuel consumption. Although the applied models are still diverse, recent studies are getting more and more integrated in the goal and scope definition rather than before. But still, some inconsistencies are present in the reviewed paper, more specifically in the definition of the functional unit and also in the selection of the different life cycle stages. Such inconsistencies make pavement LCA results difficult to compare and most importantly limit their usefulness in a decision-making process.

Important challenges and research opportunities, (as short and medium-term perspective) were also highlighted along the paper. Referring to ISO 14040 and 14044, these challenges corresponds specifically the inventory collection stage and also to the environmental impact assessment and interpretation stages. Research opportunities related to the inventory phase are summarized in Table 2.4, mainly encompass the following parameters which need to be quantified and integrated in pavement LCA: pavement surface roughness; noise; lighting needs; albedo effect; carbonation and Earthworks.

The integration of the important components of the pavement use phase has not be investigated in a policy-making level yet. Development of a consequential LCA (CLCA) framework may be helpful to evaluate the large-scale implications of shifting from one alternative to another in pavement construction, considering the intersectoral relationship of construction industry, residential and commercial and transportation sector. As an example, integrating lighting needs as a consequence to different type of pavement open rooms the CLCA development. The consequential LCA is the appropriate methodology to integrate changes in flows which are not directly (physically) connected the compared systems (pavements in our case).

To have an accurate resolution on the consequential impacts of pavement alternatives, we need to understand several time-dependent parameters in the pavement life cycle. As an example, the temporal behavior of carbonation in order to capture the variation of captured CO_2 as a function of time and such patterns should be integrated within the LCA model. As a result, dynamic LCA has to be developed by disaggregating different flows, including the captured CO_2 as a function of time. Sensitivity and uncertainty analysis were also highly recommended in future pavement LCA because of the diversity materials options, construction methods, and so on, as they can only be captured by such type of analysis. Finally, the highlighted achievements for future LCA research will make possible for policy makers, project managers, construction engineers and users have a prospective perspective in sustainable development of the pavement sector.

Table 2.4. Summary of the challenges and research opportunities in life cycle inventory of pavement

Parameter	Challenges	Research opportunities
Pavement surface roughness	-Consequences of surface roughness on indirect emissions induced by vehicles have not been studied	-Effect of surface roughness on vehicle repair and maintenance and tire wear must be included as a consequence of surface roughness
Noise	-Generated noise in pavement LCA from cradle to grave has not been measured and integrated to quantify the human health impacts.	-Noise as a consequential use of different types of pavement needs to be investigated. -Noise integration within LCA databases need to be developed.
Lighting	-Lighting as a consequence of pavement use has not been included in recent studies.	-Incorporation and calculation of lighting energy in study of pavements with various types of materials by developing a consequential LCA[h] is missing. -Temporal variation lighting energy consumption over time during the life span of the pavement needs to be developed and integrated
Albedo effect	-Implementation effects of new technologies of pavement surface on albedo are missing -A consensus decision regarding to albedo effect of concrete has not been made yet.	-Further research on albedo effect of concrete and its integration within LCA needs to be done.
Carbonation	-Carbonation of concrete pavements has not been considered in pavement LCA.	-A constitutive model on carbonation of concern as a function of CO_2 concentration, ambient temperature, relative humidity, concrete constituents and debris grading of demolished concrete at the EOL is recommended.
Earthworks	-Various volume of under layers earthworks as a result of different rigidity of pavement has not been evaluated in comparative studies.	-Significant amount of emission induced by earthworks needs to be assessed and integrated in LCA.

[h]By consequential LCA, we mean study the environmental consequences of possible (future) changes between alternative product systems [12] C. Calwell, California State Fuel-Efficient Tire Report, Volume II, California Energy Commission, January, 2003.

CHAPTER 3 PROBLEM STAEMENT AND PROJECT DEFINITION

3.1 Problem statement

The critical review of the pavement studies showed the importance and the significance of considering dynamic changes of demands and supplies in the life cycle. The temporal distribution of impacts within the pavement life cycle is not fully captured in previous studies, as inventory results are aggregated. The issue of neglecting dynamic changes in pavement LCA studies can be manifested in the results in two ways:

1. Apart from being complex and requiring the prediction of future technological improvements, the emission factors and fuel consumption or efficiency improvements are disregarded.
2. Considering the long use phase of pavements, a certain number of parameters are changing as a function of time and pavement use. A simplification in capturing these dynamic changes in parameters may result in an inaccurate estimation of the environmental impacts in the use phase.

These dynamic changes can be found in these examples. The extra fuel consumption of vehicles is linked to an increase in pavement surface roughness over the life cycle. The surface roughness after initial construction has been considered as the base value of roughness, and the emissions from fuel consumption are calculated based on the progressive increase from that initial roughness. While it may be more coherent to analyze the dynamic fuel consumption of vehicles between the pavement alternatives in comparative studies. The RF effect of albedo has been generally calculated as the estimated difference between the albedo of pavement and that of a fully reflective surface [162]. Given that all the life cycle phases are considered in a relative format, it is coherent to quantify all the burdens based on the same base case to attain a sensible and valid contribution analysis of the phases in the impact categories.

The traditional approach of LCA, namely attributional LCA (ALCA), has been deployed to assess the environmental impacts of the pavement. However, the market and consumer behavior cannot be captured when using ALCA and thus, the coherent approach in decision-making in short and long-term perspectives is consequential LCA (CLCA). Conducting an LCA with a consequential framework prevents separating a product system from the rest of the technosphere within an economic framework. Therefore, this CLCA study can consider the consequences beyond the system boundaries, i.e. in the parts that have been allocated or simplified through averaging. In addition, generally in CLCA framework, an alternative (ALT) case will replace a base case, namely a business-as-usual (BAU) scenario. Therefore, the BAU case seems to be a consistent and steady baseline for all the time-dependent parameters in the use phase of pavements.

The inclusion of a dynamic structure in consequential assessments is not a recent recommendation, however, the efforts were insufficient. In fact, a review of current CLCA studies shows that these methods still lack the representation of the system dynamics, which is considered crucial for the accuracy of the results and for the enhancement of the decision-making process [36]. The changes in physical conditions of pavements can vary as a function of time. Therefore, considering the relatively long service life of pavements, the corresponding life cycle inventory is time-dependent. In addition, it seems essential to include a dynamic model in CLCA of pavement, so that the LCA models would be able to better reflect the relevance of future scenarios. In fact, the impacts of emissions are merely the arithmetic sum of all current and future activities. Particularly in global warming potential (GWP) impact, the severity of the emissions depends on the GHG type, quantity and timing of the induced GHGs [163, 164]. To assess the environmental impacts of the previously developed dynamic characterization factors (CFs), a dynamic life cycle inventory (DLCI) with a time-series structure is required.

Pavement LCA studies incorporate various sources of uncertainty and variability. Summarizing the literature of uncertainty and variability in pavement LCAs, because an interdependent effect of the uncertainty sources exists in the analysis, it is unsound to single them out in the study [159]. Indeed, in comparative studies and particularly in pavement life cycle studies, sources of dispersion are correlated with each other. For example, if an LCA evaluates asphalt and concrete, the uncertainties related to gravel and sand production are assumed to be identical, and only the variability associated with the amount of sand in the mix design of the asphalt or concrete should be considered. Evidence of significant differences in the absolute and relative results are presented by Henriksson et al. [161], showing that absolute uncertainties led to a change in the conclusion when independent sampling was chosen in each iteration. The combined effect of uncertainty and variability sources can provide an insight on the robustness of the conclusions. On the other hand, the individual effects of the sources can clarify where the major variations come from and therefore, in terms of treatment, which source should be prioritized. So far, to the best knowledge of the author, no method has been proposed to consistently assess the variability and uncertainty sources of pavements LCAs either in CLCA or ALCA. In this sense, a flexible procedure applicable to LCA software packages or other complimentary add-ons is required to include all the possible uncertainties and variabilities with various probability distributions in the analysis.

3.2 Research objectives

In this dissertation, a novel and consistent method for assessing the individual and combined effects of uncertainty and variability sources is proposed. This method can be applied to both ALCA and CLCA studies. In addition, a dynamic CLCA method is developed to overcome the discussed issues regarding the time-dependent parameters. Applying this model to pavement case studies can facilitate the decision-making process to provide a more accurate assessment technique. Hence, the following sub-objectives were considered in this dissertation:

- Propose a consistent method, applicable to both ALCA and CLCA, to evaluate the uncertainty and variability sources in pavement LCA considering the interdependency of parameters (Chapter 4).
- Develop a dynamic consequential framework to assess the environmental consequences of pavements and including the uncertainty analysis framework proposed in the previous stage (Chapter 5).

In this dissertation, a dynamic consequential model was developed to overcome with the stated problems. The model comprises a dynamic life cycle inventory framework to reflect the true changes in the world. Moreover, an uncertainty analysis model was proposed to evaluate the individually and combinedly assess various uncertainty and variability sources in the pavement life cycle.

3.3 Research questions

To achieve the above objectives, several questions concerning the dynamic consequential modelling and the uncertainty and variability analysis have been framed as follows:

a) Uncertainty and variability analysis

- Depending on the available data, what is the individual and combined effects of uncertainty and variability sources in both attributional and consequential LCA of pavement?
- What is the contribution of each uncertainty and variability source to the variance of the results?

b) Dynamic consequential modeling

- How does the increasing accuracy in the results through the implementation of consequential dynamic inventory framework can divert the results compared to the static framework?
- Considering the provided dynamic inventory, how the accuracy of the results can be improved through the application of dynamic characterization factors can?

CHAPTER 4 ASSESSING THE INDIVIDUAL AND COMBINED EFFECTS OF UNCERTAINTY AND VARIABILITY SOURCES IN COMPARATIVE LCA OF PAVEMENTS

Avant-propos

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Titre français: Évaluation de la contribution individuelles et combinées des sources d'incertitude et de variabilité dans l'ACV des chaussées

Contribution au document: Présenter une méthode pour comprendre les sources de variation les plus déterminante dans chaque catégorie de dommages.

Résumé français

Plusieurs efforts ont été réalisés pour intégrer les sources d'incertitude et de variabilité des données dans l'analyse du cycle de vie (ACV) des chaussées. Cependant, aucune méthode n'a été proposée pour considérer simultanément la qualité des données, les choix méthodologiques et la variabilité des matériaux et des méthodes de construction sans avoir besoin d'utiliser un logiciel complémentaire. Ce projet de recherche vise à développer et implémenter une méthode flexible, applicable aux logiciels d'ACV, pour évaluer les effets de ces sources sur la robustesse des conclusions.

Une simulation de Monte Carlo a été effectuée et appliquée à une ACV comparative de la chaussée pour évaluer le scénario le moins dommageable sur l'environnement ainsi que la robustesse des conclusions. Premièrement, les incertitudes des résultats ont été estimées en considérant la qualité des données à l'aide de la base de données ecoinvent. Deuxièmement, la variabilité des matériaux, des méthodes de construction et des étapes de réparation du cycle de vie de la chaussée a également été incluse dans l'analyse en assignant des distributions de probabilité uniformes continues à chaque variable. Troisièmement, la probabilité de choix méthodologiques a été modélisée à l'aide de distributions uniformes. Les effets individuels et combinés de ces sources d'incertitude et de variabilité ont été évalués dans une ACV comparative des chaussées en asphalte et en béton dans une région froide comme le Québec (Canada).

Les résultats de la simulation de Monte Carlo montrent que les méthodes d'allocation peuvent changer le scénario le plus favorable dans quatre catégories d'impact. Ces catégories sont principalement dominées par la chaîne d'approvisionnement du pétrole brut. La variabilité des matériaux et des méthodes de construction peut modifier le scénario favorable dans les catégories de dommages, à savoir la santé humaine et le réchauffement climatique. En outre, l'incertitude des paramètres entraine un effet significatif sur la conclusion du scénario favorable en matière de qualité de l'écosystème. Cela est dû aux scores qualitatifs donnés à l'incertitude géographique des flux élémentaires qui contribuent majoritairement à cette catégorie (par exemple le zinc). L'effet simultané des sources d'incertitude et de variabilité empêche le décideur d'arriver à une conclusion définitive sur la qualité de l'écosystème, la santé humaine et les effets du réchauffement climatique.

Cette étude démontre qu'il est possible d'évaluer les effets cumulés de sources communes d'incertitude et de variabilité à l'aide d'un logiciel ACV commercial qui permet des simulations de Monte Carlo. Sur la base de la variabilité et de l'incertitude des résultats, l'atteinte d'une certaine conclusion sera spécifique à chaque cas, tant aux catégories d’impact qu'aux catégories de dommage. L’amélioration de la qualité des données d'inventaire peut être une solution pour réduire les incertitudes sur la santé humaine, la qualité de l'écosystème et le réchauffement climatique de l'ACV d’une chaussée. Cette amélioration peut être obtenue en évitant l'adaptation d'un processus similaire pour correspondre au processus considéré et en utilisant des valeurs d’efficacités de méthode de construction et de production de matériaux de construction plus représentatives. L'efficacité de ces solutions doit être évaluée dans de futures études. De plus, des recherches supplémentaires sur la variabilité des processus de base (par exemple, la source de matières premières et de bitume) peuvent apporter de nouvelles perspectives dans l’interprétation des résultats liés à l'incertitude.

Mots-clés : Analyse d'incertitude, simulation de Monte Carlo, choix méthodologiques, qualité des données, variabilité technologique, chaussée en béton, chaussée en asphalte.

4.1 Abstract

Purpose Several efforts have been made to incorporate uncertainty and variability sources in the life cycle assessment (LCA) of pavements. However, no method has been proposed to consider data quality, methodological choices, and variability in construction materials and methods simultaneously and without the need to use any complementary software. This dissertation aims to develop and implement a flexible method, which is applicable to LCA software, to assess the effects of these sources on the robustness of conclusions.

Methods A Monte Carlo analysis was conducted and applied to a comparative LCA of pavements to assess the preferred scenario and robustness of the conclusions. The uncertainty of results was first estimated by considering data quality using the ecoinvent database. Moreover, the variability of materials, construction methods and repair stages of the pavement's life cycle was included in the analysis by assigning continuous uniform probability distributions to each variable. Ultimately, the probability of methodological choices was modeled using discrete uniform distributions. The individual and combined effects of these uncertainty and variability sources were assessed in a comparative LCA of asphalt and concrete pavements in a cold region such as Quebec (Canada).

Results and Discussion The results of the Monte Carlo analysis show that the allocation choices can change the environmentally preferred scenario in four midpoint categories. These categories are majorly dominated by crude oil supply chain. The variability in construction materials and methods can change the preferred scenario in damage categories, namely human health and global warming. Besides, parameter uncertainty has a significant effect on the conclusion of preferred scenario in ecosystem quality. It is due to the worst qualitative scores that are given to the geographical uncertainty of the elementary flow that majorly contributes to this category (i.e. zinc). The simultaneous effect of the uncertainty and variability sources prevents the decision-maker from reaching a robust conclusion about the ecosystem quality, human health, and global warming effects.

Conclusions and outlook This dissertation demonstrates that it is feasible to assess the accumulated effects of common uncertainty and variability source using commercial LCA

software including the Monte Carlo simulation. Based on the variability and uncertainty of the results, reaching a certain conclusion will be case specific both in midpoint and endpoint levels. Increasing the quality of inventory can be a solution for decreasing the uncertainties about human health, ecosystem quality and global warming of pavement LCA. This improvement can be achieved through avoiding adaptation of a similar process to match the considered process and using practical construction efficiencies and realistic construction materials. The effectiveness of these tasks needs to be assessed in future studies. In addition, further research on the variability of background processes (e.g. source of raw materials and bitumen) can bring a new outlook for the uncertainty-related results.

Keywords: Uncertainty analysis, Monte Carlo simulation, Methodological choices, Data quality, Technological variability, Concrete pavement, Asphalt pavement.

4.2 Introduction

Various construction materials used in infrastructure construction, such as pavements, cause substantial environmental impacts (e.g., contributing approximately 75 million metric tons of carbon dioxide (CO_2) emissions, which is approximately 5% of the total transportation emissions [2]). Pavement construction varies from one case to another, even if the basic structural design inputs are the same. Moreover, assessment of the environmental impacts of pavements using LCA also incorporates different types of uncertainties. The types of uncertainty are well addressed by researchers in the context of pavement studies [46, 160] and more generally in the environmental modeling framework of any product or service [157, 165]. One should note that variability stems from inherent changes in the real world, where LCA calculation has not yet been applied to the data (e.g., true differences in production technologies, materials or regions). However, uncertainty is related to converting real-world data to LCA outcomes, where simplification of reality, introduction of subjective choices or lack of precision in estimates of parameters occur and are included in the LCA models [157]. In addition, uncertainty can be reduced with additional measurements, whereas variability inherently exists in the environment and cannot be reduced by additional research [158]. In fact, to achieve a consistent comparison of existing pavement alternatives, it is essential to consider and understand the impacts of variability and uncertainty on the life cycle of a product. Although no methodology is specified, ISO 14044 recommends conducting local sensitivity (e.g., one at a time) and uncertainty analyses in comparative studies intended for public disclosure [14]. Therefore, a comprehensive method is required to meet the ISO specification.

Uncertainties are often associated with the collected data in pavement life cycle stages. For example, the quality of background processes is considered in the ecoinvent database with respect to completeness, reliability, temporal correlation, geographical correlation, and further technological correlation [166], which are incorporated into the database by the pedigree matrix [121]. Another source of uncertainty is methodological choices in the system boundary (i.e., what to include in the foreground unit processes) and allocation rule selections, which are frequent in LCA studies. Moreover, for the case of pavement, various materials and construction methods are used in road construction and maintenance. Certain alternatives in pavement construction include recycled materials and new technologies (e.g., warm-mix additives) in asphalt [126, 167] and concrete pavements [168, 169]. These pavement construction methods and materials affect the pavement lifetime and the maintenance and repair schedule and consequently affect the life cycle environmental impacts.

Certain pavement LCA studies have covered uncertainty due to data quality using the pedigree matrix in different versions of the ecoinvent database [3, 53, 170]. However, few studies have considered the other types of uncertainties in the pavement life cycle stages. Researchers have commonly selected deterministic scenario analysis to evaluate the effect of variability and uncertainty parameters in the pavement life cycle. For example, Jullien et al. considered the effect of a single variability source (e.g., bitumen content or the replacement level of reclaimed asphalt pavement) to observe the changes in the environmental impacts of pavement [22]. In a study by Larrea-Gallegos et al., four different scenarios of carbon stock in forest land (an uncertainty source) and four levels of daily traffic (a variability source) were implemented for an unpaved road [171]. Consequently, the calculations were repeated 16 times to assess the extent to which the results can change. Huang et al. used the same approach in allocation choices of bitumen and blast furnace slag (uncertainty sources) and reported that different methods of allocation for bitumen could only change the fossil fuel results [172]. However, a combination of these normative choices and relative changes might occur simultaneously. In fact, single-parameter analysis might not reflect the combined effects of all variability and uncertainty sources for pavement comparison.

Wang et al. examined the uncertainty of different datasets for life cycle inventory of pavement construction materials using deterministic scenario analysis and reported that conclusions related to the preferred scenario from a global warming point of view are changed by implementing different datasets and databases, such as ecoinvent [173], USLCI [174], Stripple [83], and Athena [80] for the foreground system [49]. Trupia et al. evaluated the effect of traffic growth, fuel efficiency, and emission factors on excessive fuel consumption of vehicles induced by pavement rolling resistance by defining three possible scenarios (i.e., base, worst and best cases) [54]. This approach is capable of considering only a limited number of scenarios and variables because the volume of calculations leads to a complicated and time-consuming procedure. Noshadravan et al. studied the same variability and uncertainty selected by Trupia et al. in addition to the pedigree matrix using Monte Carlo simulation [46]. The results showed an overlap between the possible ranges of global warming values of asphalt and concrete. Gregory et al. developed a model for the propagation of pavement life cycle variability in addition to the data quality [160] that is capable of considering the probabilities of the input and output values using lognormal distributions.

Summarizing the literature of uncertainty and variability in pavement LCAs, because an interdependent effect of the uncertainty sources exists in the analysis, it is unsound to single them out in the study [159]. Furthermore, use of different joint software packages as a complementary tool to conduct probabilistic scenario analysis has many advantages but is time-consuming for practitioners and requires sufficient resources. For example, Gregory et al. implemented different scenarios for a hand dryer using Microsoft Excel with Crystal Ball for the Monte Carlo method and the same inventory and unit process data used in the assessment of parameter uncertainty in SimaPro [175]. Aktas and Bilec used @RISK software to assess effects of the uncertainty in variables such as building lifetime on the obtained results [176]. Furthermore, the uncertainty of different methodological choices, such as allocation of bitumen and byproducts in pavement construction, has not been included in the probabilistic analysis. When all sources of uncertainties are applied in the analysis, the resulting “absolute” uncertainties often become enormous, making it difficult to draw conclusions in comparative studies [160]. In addition, in comparative studies and particularly in pavement life cycle studies, sources of dispersion are correlated with each other. For example, if an LCA evaluates asphalt and concrete, the uncertainties related to gravel and sand production are assumed to be identical, and only the variability associated with the amount of sand in the mix design of the asphalt or concrete should be considered. Evidence of significant differences in the absolute and relative results are presented by Henriksson et al. [161], showing that absolute uncertainties led to an entirely different conclusion when independent sampling was chosen in each iteration. In this sense, a flexible procedure applicable to LCA software is required to include all of the possible uncertainties with various probability distributions in the analysis.

In this study, a comparative cradle-to-grave LCA of hot-mix asphalt and jointed plain concrete pavements is performed starting from a goal and scope definition and followed by inventory analysis, life-cycle impact assessment (LCIA), and interpretation. A viable method is proposed to assess the uncertainty derived from the parameters, the variability of construction materials and methods, and the methodological choices (allocation rules). The effects on the midpoint and endpoint results are analyzed using Monte Carlo simulation. The uncertainties in the characterization factors of impact assessment method were not included and are left for future research studies.

4.3 Methodology

4.3.1 Uncertainty model description

Several uncertainty propagation methods have been proposed and between those, Tyler series expansion (analytical) and Monte Carlo simulation (Numerical) are adopted to LCA databases. In the analytical approach, distribution type and parameters or outputs cannot be determined, and the outcomes are fairly rigid and limited to simple linear models. The proposed method is first introduced in this section. Monte Carlo analysis, which is the most conventional method used in LCA to assess the propagation of the uncertainty of unit process data, is applied [165]. This methodology can be easily implemented in different LCA software packages, such as SimaPro, without the need for any joint software. The sampling method was performed using Monte Carlo simulation, which is a set of computational algorithms that rely on repeated random sampling to obtain numerical results. Therefore, a probability distribution was assigned to each variable included in the analysis.

For the scenario uncertainty, whether allocation choices or system boundaries selection (inclusion of unit processes in the foreground system), the possible scenarios were considered as discrete choices. A uniform distribution was hence assigned to each methodological choice (e.g., allocation method), as shown in Figure 4.1. The probability of the methodological choice scenarios was calculated using Eq. 4.1.

$$\mathrm{P}(\mathrm{A}_x) = \begin{cases} \mathrm{P}(\mathrm{A}_1) = \frac{\mathrm{X}_1 - \mathrm{X}_0}{\mathrm{X}_n - \mathrm{X}_0} \\ \mathrm{P}(\mathrm{A}_2) = \frac{\mathrm{X}_2 - \mathrm{X}_1}{\mathrm{X}_n - \mathrm{X}_0} \\ \mathrm{P}(\mathrm{A}_3) = \frac{\mathrm{X}_3 - \mathrm{X}_2}{\mathrm{X}_n - \mathrm{X}_0} \\ \quad\vdots \\ \mathrm{P}(\mathrm{A}_n) = \frac{\mathrm{X}_n - \mathrm{X}_{n-1}}{\mathrm{X}_n - \mathrm{X}_0} \\ 0 \quad for \quad x < \mathrm{X}_0 \; and \; x > \mathrm{X}_n \end{cases} \tag{4.1}$$

where A_x is the scenario of "x" for method "A". For example, "A" can be the allocation of bitumen in crude oil extraction and refinery, and "n" represents number of possible scenarios, such as allocation based on mass, economy, etc. It should be noted that the methodological preference of each scenario could be adjusted by changing the intervals between the values of X_i in the distribution (e.g., the interval between X_0 and X_1 can be increased to increase the probability of scenario A) (Figure 4.1).

Variability sources are those input parameters that is not do with the LCA calculation but more relevant to the inherent changes in the world. To conduct the uncertainty analysis on the possible variability of each unit process, a continuous uniform distribution is defined according to Eq. 4.2.

$$P(y) = \begin{cases} \frac{1}{Y_1 - Y_0} & for\ Y_0 \leq y \leq Y_1 \\ 0 & for\ \ y < Y_0\ and\ \ y > Y_1 \end{cases} \tag{4.2}$$

where Y_0 and Y_1 are the minimum and maximum values possible for material or method "y", respectively. The values Y_0 and Y_1 are obtained from the possible range of changes in the input data. All of the variability sources have a uniform distribution because it is assumed that all values are equally likely to be considered (in the absence of alternative information). The probability distribution can be changed if the primary data of the variability follow other functions (normal, lognormal, etc.).

Parameter uncertainty is the most conventional type of uncertainty and has been studied in various LCA case studies. To date, the pedigree matrix has been primarily used to code the qualitative judgments into numerical scales with consideration of criteria, such as reliability, completeness, and temporal, geographical and technological correlation of the input data [177]. For each criterion, an uncertainty factor is calculated by analyzing data from different sources. The variance (σ) of the parameter distributions (i.e., commonly, a lognormal distribution) is calculated based on Eq. 4.3:

$$\sigma^2 = \sum_{n=1}^{6} \sigma_n^2 \tag{4.3}$$

where σ_1 to σ_5 are the uncertainty factors (variance) of reliability, completeness, temporal correlation, geographical correlation, and technological correlation, respectively. In addition, a

basic uncertainty factor (σ_6) is also considered whether the process represents an environmental flow to the technosphere or emissions (i.e., applied to intermediate and elementary flows when no sampled data are available for combustion, process emissions, and agricultural emissions) [121]. It should be noted that this equation is only valid for lognormal distributions.
Using this methodology enable the LCA practitioners to consider the following interdependency between parameters and sources:

a) *Dependency of sampling in a unit process of life cycle of compared products within an uncertainty source*

As a specific value is assigned to an environmental or economical flow in a Monte Carlo run, the same value should be applied to all other places that this unit process is used along with all the products life cycle in the comparative studies. For example, all the emissions and consumptions in aggregates production should be derived from the same set of sample values for both unit process data in each Monte Carlo run in the comparative study of asphalt and concrete. Likewise, this dependency in sampling should be considered to allocation choices when considering the uncertainty due to the methodological choices, namely, when a mass allocation is selected for asphalt life cycle, the same allocation rule based on mass should be applied to the concrete life cycle.

b) *Dependency of sampling in different unit processes of a product life cycle within an uncertainty source*

When the value of a parameter will vary within a source of uncertainty or variability, it may influence another parameter value. For example, the aggregates mass should be adjusted when there is a change in mass of binder in in one cubic meter of asphalt or concrete. Indeed, the decrease in binder mass as a result of variability or uncertainty will result in an increase in aggregates mass to preserve one cubic meter of the mixture. This dependency id considered in this method by parametrizing the aggregates mass value as a function density and binder mass.

c) Dependency of sampling between uncertainty and variability sources

In some cases, sources of uncertainty and variability are correlated. In this regard, the sources dependency should be considered in the analysis. For example, an uncertainty due to methodological choices may affect the parameter uncertainty. Imagine the case that there are two allocation choices (considered as two scenarios) and the flows in each scenario are different. Therefore, when one of the scenarios is chosen in an iteration, the parameter uncertainty corresponding to the flows in that scenario is taken to account in that iteration.

All of the probability distributions were analyzed using Monte Carlo simulation to assess the uncertainty of different sources with consideration of relative uncertainty (i.e., pair-wise analysis), and only the difference between asphalt (alternative A) and concrete (alternative B) was considered for each iteration (A-B) in the SimaPro software. Readers are referred to Section 3 in the Supplementary Information for additional details on the modeling procedure in the software.

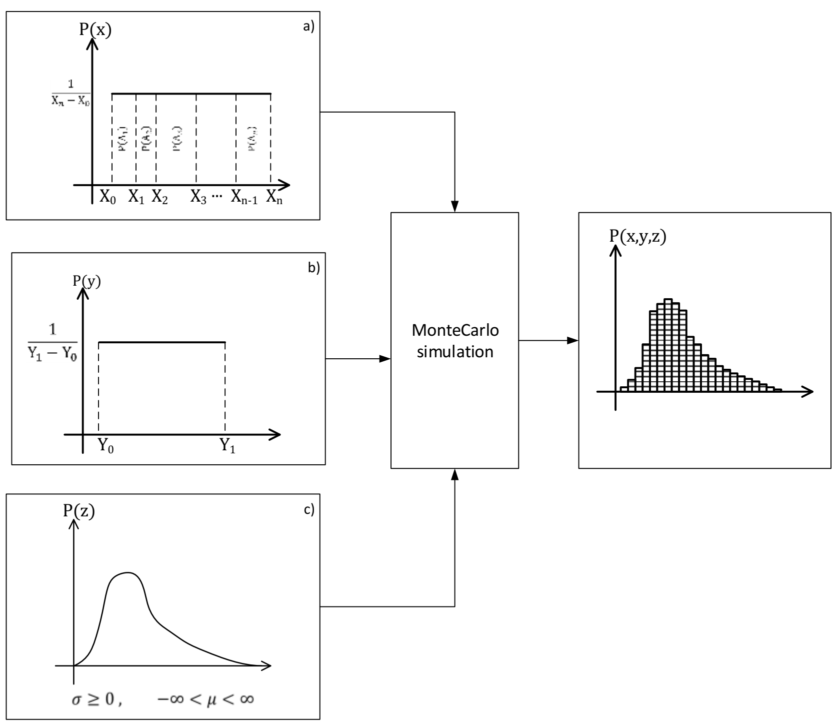

Figure 4.1. General framework of a) scenario uncertainty, b) variability in construction materials and methods, and c) parameter uncertainty modeling

4.4 Case study: Asphalt and concrete pavements

4.4.1 Goal and scope definition

The purpose of this study is to highlight the potential environmental impacts of jointed plain concrete and hot-mix asphalt pavements and to apply the proposed methodology in a comparative study. The spatial context was restricted to the cold environment that prevails in the province of Quebec (Canada). According to ISO 14044, if two or more product systems are compared using LCA, the same functional unit must be selected [14]. In previous reviews of pavement LCA, it was recommended that the pavement functional unit should include the physical properties of the pavement system, including design, structural components, and material properties as well as effective external factors of the pavement such as traffic load [162]. In fact, in addition to the pavement length, its lifetime must be considered as a key parameter in defining the primary function of the pavement [162]. In this study, the functional unit was defined as "providing a path for traffic service for 20 000 AADT[9], including 5% of the truck, over 1 km length of a two lanes road in Quebec urban area and for a 50-year lifespan".

4.4.2 Inventory analysis

This study is primarily focused on the environmental analysis of the material production, pavement construction, repair and maintenance, and end-of-life stages. The following descriptions present the unit processes in each stage. The details of each stage are explained Section 1.1, and the system boundary is illustrated in Figure A2.1 in Appendix 2 in the Supplementary Information. The ecoinvent v.3.2 database was applied in modeling the background processes using cut-off modeling assumptions [178].

A. Materials production: This stage includes all production processes of the materials, from raw material extraction to transformation into the final product.

B. Pavement construction: This phase includes all of the execution phases in the construction of the surface and the sub-layers, including equipment fuel consumption and transportation of processed materials to the construction site.

[9] Annual Average Daily Traffic.

C. Maintenance and repair (M&R): These tasks are essential for recovering the functionality of the pavements over their service life. As a component of the repair strategy, the Quebec transportation government plans to resurface concrete pavement after 39 years [3], and in the case of asphalt pavement, the repair steps are planned at specific time intervals using hot-mix asphalt materials (Tables A2.5 and A2.6 in Supplementary Information).

D. End-of-life: This stage refers to material recycling and landfilling. The activities related to this stage are demolition and transportation of waste, consumption, and emissions attributed to equipment, and waste landfilling impacts. A proportion of the demolished materials is recyclable and will be used in another life cycle.

4.4.3 Life cycle impact assessment method

Life cycle impact assessment (LCIA) was performed using the IMPACT 2002+ methodology. The results were presented using the midpoint and endpoint impact categories [179]. According to ISO 14044, sensitivity analysis determining the influence of variations in the assumptions, methods (such as the LCIA method) and data on the results [14]. Therefore, a sensitivity analysis of the midpoint results was performed in which the IMPACT 2002+ method was replaced by TRACI V.2.1 to investigate the effect of the LCIA methods in different geographical contexts.

4.4.4 Uncertainty and variability analyses of the inventory data

The literature of pavement LCA considers uncertainty and variability analyses only in the inventory data. Therefore, uncertainty in the characterization methods is not captured in this work. For the interpretation stage, a Monte Carlo simulation was performed to assess the effect of both uncertainty and variability on all midpoint and endpoint results of IMPACT 2002+. The procedure for applying the proposed method on a pavement case study is presented as follows.

a) Scenario uncertainty

According to ISO 14044, uncertainty analysis should consider the cumulative effects of model imprecision, input uncertainty, and data variability [14]. The SimaPro software was used to conduct a Monte Carlo analysis using 2500 iterations.

Mass and economic allocation methods were examined for crude oil extraction and refinery and for limestone powder production, according to Table 4.1. It should be noted that when a specific allocation method is selected in each run, this method is considered for all the foreground system of two scenarios. In addition, the variability of limestone powder sources was considered. In the first scenario, limestone powder was considered a byproduct of stone cutting and crushing (treated as waste or allocated by mass or economics), whereas, in the second scenario, it was assumed that limestone powder was the reference product of limestone crushing and intergrinding. All of these normative scenarios for bitumen and limestone powder were assessed in the pavement using the methodology presented in Section 2.1. The methodological preferences for all choices were considered equal in this case study.

Table 4.1. Definition of different scenarios for allocation of bitumen and limestone production

Process	Allocation method (probability of choice)			
Crude oil extraction	Mass (50%)			Economic (50%)
Crude oil refinery	Mass (50%)			Economic (50%)
Limestone powder production	By-product (50%)			Main product (50%)
	Waste (16.7%)	Mass (16.7%)	Economic (16.7%)	

b) Variability in construction materials and methods

The variability of processes was presented as the possible variations in materials and in construction and repair methods during the life cycle stages. For example, in the Canadian context, it is possible to substitute up to 15% of portland cement with interground limestone [180]. In hot-mix asphalt pavements, the mass of bitumen used as binder usually varies between 4 and 6% of the total asphalt mass based on the properties of fine aggregates and filler. The change in the binder content leads to alteration of the mass of other mixture ingredients such as coarse and fine aggregates in a constant volume due to the difference in material density. Moreover, the pavement lifetime can change as a consequence of premature failure in materials (e.g., low quality of placement during construction and maintenance can result in premature deterioration due to cold or hot weather or severe winter). As a result of this change in the age of the pavement life, the value of the reference flows fulfilling the functional unit will be changed (referring to Section 2.1).

Other variations refer to machinery efficiency during pavement construction and repair and the proportion of recyclable materials at the end of life or other stages. Certain researchers have already investigated a limited section of these uncertainty sources but only from an emergy perspective [62]. Uniform distributions were used to consider the lower and higher values of the materials and construction methods used in the pavement's life cycle. For the asphalt and concrete scenarios, eight and nine sources of variability were included, respectively. These sources of variability are listed in the Supplementary Information. For additional information on the details of variability in the processes, readers are referred to Table A2.1 and A2.2 (see Supplementary information).

c) Parameter uncertainty

The probability distributions for parameter uncertainties were adopted from the ecoinvent v.3.2 database [178]. This source is characterized by all of the elementary and intermediate flows that frequently have a lognormal distribution (because few inventories exist with normal, triangular and undefined distributions). Dependent sampling is applied on SimaPro when considering the parameter uncertainty using the ecoinvent database. It should be noted that the included uncertainty in the ecoinvent database (pedigree matrix) is not a measure of the real variability of the processes (i.e., statistically determined using actual measures captured during data collection) [181]. Nevertheless, the quality of the used data was determined by the dataset provider based on origin, method of collection, and representativeness. The completeness, reliability, temporal correlation, geographical correlation, and further technological correlation of the obtained data were included in the pedigree matrix (see Section 3 in Supplementary information).

d) Combined effect of variability and uncertainty sources

All the three sources of uncertainty and variability were included in the Monte Carlo simulation. Therefore, for each iteration, an allocation choice was selected for both systems and at the same time, the parameters uncertainty defined by pedigree matrix was included in addition to the variability of construction materials and methods. Readers are referred to Section 3 in the Supplementary Information for additional details on the modeling procedure in the software.

4.5 Results and discussion

4.5.1 Comparative results

Figure 4.2 illustrates the comparative midpoint results of concrete and asphalt pavements in the province of Quebec. The concrete scenario has a slightly lower impact than asphalt in eight impact categories. However, the aquatic acidification impacts are similar. It can also be observed that the material production stage plays a significant role in the life cycle impacts of the pavements. The range of contribution for material production in the total life cycle impacts is between 43% (in the case of terrestrial ecotoxicity) and 90% (in the case of mineral extraction) for concrete and 42% (terrestrial ecotoxicity) and 94% (mineral extraction) for asphalt. It is worth mentioning that the material production includes extraction of raw materials and material transport to plants as well as their production (e.g., asphalt or concrete production).

If the material preparation before delivery to the plant and production in the plant is considered as a separate life cycle stage (namely, the production stage), the contribution of the concrete production stage is as low as 7% in all impact categories. The contribution of the production stage in the asphalt scenario (transportation of asphalt materials to the plants and energy consumption and emissions of the asphalt plant) is more significant compared with the concrete scenario (Figure A2.5 in Supplementary Information), particularly in global warming (20% of the total impact). Indeed, a significant volume of asphalt materials is required for pavement construction (1780 m^3) and repair (2190 m^3) in the hot-mix asphalt scenario. However, a considerable amount of fuel (285 MJ/t of asphalt) is needed to supply the energy for adjustment of the mixture temperature and aggregate pre-heating [83]. Thus, the contribution of this unit process, which represents 72% of all CO_2eq in asphalt production, is significant in the life cycle environmental impacts of asphalt. A similar result from another case study confirms the global warming contribution of asphalt plant emissions in the production stage (71%) in the U.S. [182]. The significant difference in non-renewable energy for concrete and asphalt stems from feedstock energy associated with bitumen (40.2 MJ/kg of bitumen) [183]. The contribution of feed stock energy in NE and R is presented in Figure A2.7 in Appendix 2.

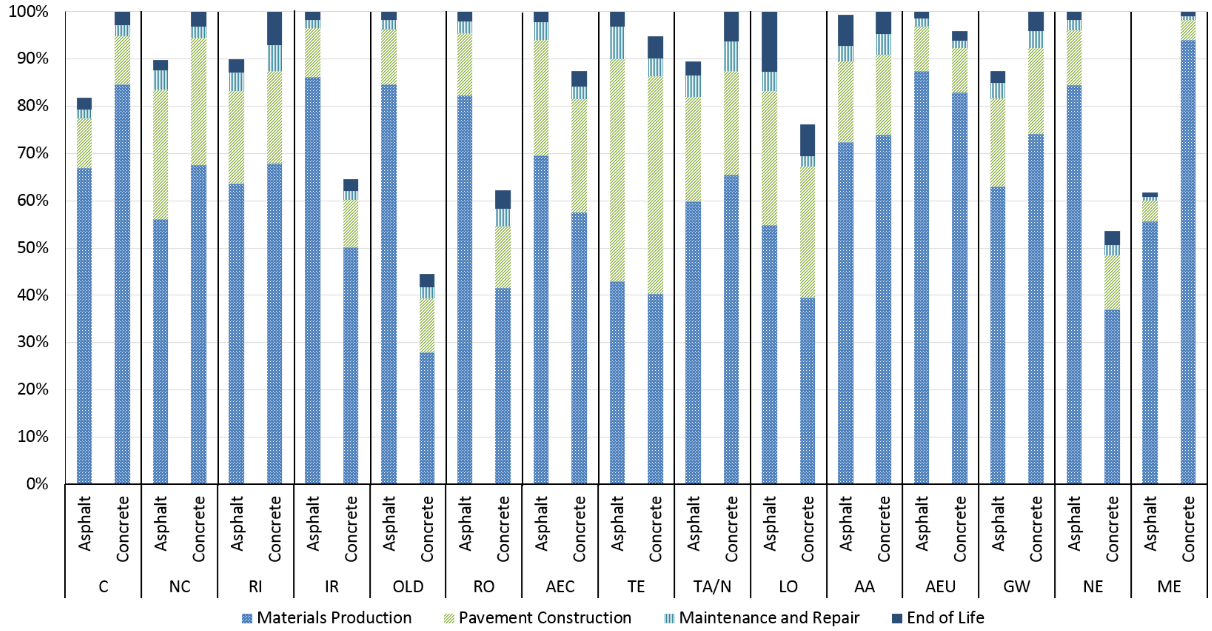

Figure 4.2. Midpoint results of concrete and asphalt scenario (IMPACT 2002+)

It was previously reported that the pavement LCA results are sensitive to the distance from the material sources to the construction site, but these processes were not one of the key drivers of the midpoint and endpoint results [169]. In this study, in addition to the material production stage, the construction stage of the asphalt life cycle has the largest contribution to terrestrial ecotoxicity (47.0%) due to a significant volume of material transport. Asphalt construction requires 1.69×10^{6} tkm of material transportation (versus 2.22×10^{5} tkm in materials production), which leads to a dominating effect of the construction stage. For the concrete scenario, similar results are observed for the same impact category. In fact, concrete pavement construction is responsible for 49.0% of terrestrial ecotoxicity emissions.

Investigating the background processes of asphalt production, the unit processes in the bitumen supply chain correspond to the major contribution in seven out of 15 midpoint categories. For example, as shown in Table 4.2, drilling waste materials in the crude oil extraction process are identified as the major contributor to aquatic and terrestrial ecotoxicity indicators. Aquatic acidification is dominated by wasted sour natural gas during onshore extraction of crude oil. Other categories that are not dominated by bitumen are mostly characterized by the contribution of pavement sub-layer transformation and material transportation between different stages. Tire and brake wear are the major contributor inventories, and their corresponding emissions (e.g., zinc and copper) are the major substances contributing to non-carcinogenic effects and terrestrial ecotoxicity of the asphalt scenario. The emissions were directly modeled using the ecoinvent database.

A significant volume of pavement sub-layers (i.e., mainly affected by frost penetration in Quebec) (Table A2.3) must be prepared and transported to the construction site. The mining and screening of base and sub-base materials also consume a considerable amount of fuel and electricity [80]. Both of these processes are key drivers of respiratory inorganics, terrestrial acidification/nutrification, and aquatic acidification. A recent study conducted on asphalt pavements using the LCIA method proposed by CML showed that the contribution of the asphalt surface layer is significant for ten midpoint categories (66-92%) [184], which is different from the results presented in this study. This difference can be explained by a lower sub-layer thickness (35 cm) and consequently a lower demand for machinery and transportation. Another asphalt pavement case study located in Australia (relatively mild and hot weather) reported a negligible (4.7%) contribution of the base and sub-base layers to the life cycle carbon footprint [170]. In the Quebec context, the contribution of the base and sub-base in this indicator is 13.3% perhaps because the sub-layers are three times thicker than those in Australia.

For the concrete scenario, the role of the base and sub-base materials is more significant compared to the asphalt. Transportation and consolidation of the base and sub-base layers require a substantial amount of diesel combustion by the machinery. Diesel combustion is the key contributor to non-renewable energy, terrestrial acidification, terrestrial nutrification, ionizing radiation, and respiratory inorganics and organics. The role of diesel in machinery is not limited to these categories. In fact, processes in the supply chain of diesel production are the major contributors to ionizing radiation and non-renewable energy categories. Other infrastructures for material transportation, tire and brake wear emissions, and diesel fuel play the most important roles in ozone layer depletion, non-carcinogenic effect, aquatic ecotoxicity, land occupation, and terrestrial ecotoxicity. The carcinogenic effect and mineral extraction of concrete are dominated by polycyclic aromatic hydrocarbons (PAHs) and nickel in crude ore, respectively. In fact, use of steel rebar for transverse and longitudinal load transfer is essential in jointed plain concrete pavements. Iron ore and coke are the main raw material inputs of steel production and thus of coke production, and a significant amount of PAHs are released into the atmosphere. In addition to iron ore and coke, chromium, manganese, and nickel crude ore are also required to produce ferroalloys during steel production. To produce 1 kg of steel, 0.045 kg of ferronickel is required [178], and production of this amount of ferronickel has greater environmental impacts than other types of metals in the life cycle of concrete pavement. It is worth mentioning that stainless coating on the rebar surface accounts for less than 0.1% contribution in all of the midpoint categories. Comparing Figure 4.2 and Figure A2.7 in the Supplementary Information, similar impact categories in TRACI and IMPACT 2002+ show consistent results except for the ecotoxicity category. Lack of an ecotoxicity characterization factor for a substantial number of substances in the TRACI LCIA method (199 versus 434 in IMPACT 2002+) is the reason behind such differences [185].

Table 4.2. Major process and substances contributor of midpoint and endpoint categories

([Carcinogenic (C), Non-carcinogenic (NC), Respiratory inorganics (RI), Ionizing radiation (IR), Ozone layer depletion (OLD), Respiratory organics (RO), Aquatic ecotoxicity (AEC), Terrestrial ecotoxicity (TE), Terrestrial acidification/nutrification (TA/N), Land occupation (LO), Aquatic acidification (AA), Aquatic eutrophication (AEU), Global warming (GW), Non-renewable energy (NE), and Mineral extraction (ME). MP and PC refer to Materials Production and Pavement Construction stage, respectively.)

Level	**Category**	**Asphalt**			**Concrete**		
		Life cycle stage	**Process (Contribution percentage)**	**Elementary flow**	**Life cycle stage**	**Process (Contribution percentage)**	**Elementary flow**
Midpoint	C	MP	Natural gas production (34.1%)	Aromatic hydrocarbons, Air (56.2%)	MP	Natural gas production (31.6%); Coke production (25.1%)	Aromatic hydrocarbons, Air (52.8%)
	NC	MP	Tire and brake wear emissions (23.8%)	Zinc, Soil (18.1%); Dioxin, 2,3,7,8 Tetrachlorodibenzo, Air (18.0%)	MP	Tire and brake wear emission (10.5%), Sinter in iron production (10.2%)	Dioxin, 2,3,7,8 Tetrachlorodibenzo, Air (25.5%)
	RI	MP	Diesel burnt in building machines (28.2%)	Nitrogen oxides, Air (44.6%)	MP	Diesel burnt in building machines (30.0%)	Nitrogen oxides, Air (45.1%)
	IR	MP	Low-level radioactive waste from petroleum (64.5%)	Carbon-14, Air (73.1%)	MP	Low-level radioactive waste from petroleum (43.7%)	Carbon-14, Air (56.7%)
	OD	MP	Petroleum production (90.7%)	Methane, bromochloridifluro, Halon 1301, Air (95.5%)	MP	Petroleum production (86.0%)	Methane, bromochloridifluro, Halon 1211, Air (91.5%)
	RO	MP	Bitumen production (28.6%); Vented natural gas in petroleum production (22.1%)	NMVOC, Air (91.2%)	MP	Diesel burnt in building machines (26.0%)	NMVOC, Air (91.9%)
	AEC	MP	Drilling waste in petroleum production (41.2%)	Aluminum, Soil (49.8%)	MP	Drilling waste in petroleum production (20.2%)	Aluminum, Soil (30.5%)
	TE	PC	Tire wear emission (34.2%), Drilling waste in petroleum production (21.1%)	Zinc, Soil (47.6%)	MP	Tire wear emission (49.0%)	Zinc, Soil (47.6%)

Level	Category	Asphalt	Concrete	Level	Category	Asphalt	Concrete
		Life cycle stage	**Process (Contribution percentage)**			**Life cycle stage**	**Process (Contribution percentage)**
Midpoint	TA/N	MP	Diesel burnt in building machines (32.1%)	Nitrogen oxides, Air (82.7%)	MP	Diesel burnt in building machines (34.2%)	Nitrogen oxides, Air (88.8%)
	LO	PC	Road infrastructure (37.5%)	Occupation, traffic area, road network, Raw (38.4%)	PC	Road infrastructure (48.5%)	Occupation, traffic area, road network, Raw (45.4%)
	AA	MP	Diesel burnt in building machines (17.9%); Heating at asphalt plant (11.3%)	Nitrogen oxides, Air (47.3%)	MP	Clinker Production (21.0%); Diesel burnt in building machines (20.9%)	Nitrogen oxides, Air (53.3%)
	AEU	MP	Petroleum production (39.5%)	Phosphate, Water (49.4%); COD, water (48.6%)	MP	Salt production (47.8%)	Phosphate, water (76.8%)
	GW	MP	Heating at asphalt plant (18.1%)	Carbon dioxide, fossil, Air (96.8%)	MP	Clinker Production (26.7%)	Carbon dioxide, fossil, Air (97.8%)
	NE	MP	Petroleum production (81.9%)	Crude oil, Raw (83.7%)	MP	Petroleum production (71.6%)	Crude oil, Raw (66.1%)
	ME	MP	Ferronickel, 25% Ni production (40.3%)	Nickel, 1.98% in silicates, 1.04% in crude oil, Raw (40.3%)	MP	Ferronickel, 25% Ni production (48.6%)	Nickel, 1.98% in silicates, 1.04% in crude oil, Raw (48.6%)
Endpoint	HH	MP	Diesel burnt in building machines (25.9%)	Nitrogen oxides, Air (40.7%)	MP	Diesel burnt in building machines (27.6%)	Nitrogen oxides, Air (41.4%)
	EQ	PC	Tire wear emission (29.2%)	Zinc, Soil (40.7%)	PC	Tire wear emission (42.0%)	Zinc, Soil (40.8%)
	CC	MP	Heating at asphalt plant (18.1%)	Carbon dioxide, fossil, Air (96.8%)	MP	Clinker Production (26.7%)	Carbon dioxide, fossil, Air (97.8%)
	R	MP	Petroleum production (81.7%)	Crude oil, Raw (83.5%)	MP	Petroleum production (70.4%)	Crude oil, Raw (65.6%)

Although most of the debates related to the environmental burdens of concrete structures center on portland cement production, this ingredient is the hotspot in only two midpoint categories (namely, global warming with 26.7% contribution and aquatic acidification with 21.0% contribution) (See Table 4.2). A similar observation was reported in a case study of concrete pavement in France [153]. Additionally, de-icing salt (47.8%) is the hotspot for aquatic eutrophication in the concrete pavement life cycle. Sulfide tailings in sodium chloride production possess a considerable amount of phosphate, which results in a substantial amount of phosphate (1.38 g/kg sodium chloride). However, the emissions of salt leached through the soil due to traffic spray processes as well as particles suspended in the air after surface drying are not considered in this study and should be included in future assessments. Further experimental studies are necessary to characterize these emissions related to consumption of de-icing salt. Hence, focusing on material processing and transportation and especially earthwork, can lead to new insights towards the determination of a sustainability strategy for concrete and asphalt pavement in cold regions such as Quebec.

Figure 4.3 presents the endpoint results for concrete and asphalt pavements. The contribution of material production is the largest among the life cycle stages of pavements in all endpoint categories, except for ecosystem quality. This result can be explained by the fact that the ecosystem quality score is composed of 85% of the terrestrial ecotoxicity (Figure A2.9) score and as described previously for the terrestrial ecotoxicity (midpoint results), the major contributor is machinery and material transportation to the construction site (in both the concrete and asphalt scenarios). Therefore, as presented in Table 4.2, the tire wear emissions from material transportation trucks dominate the result for ecosystem quality.

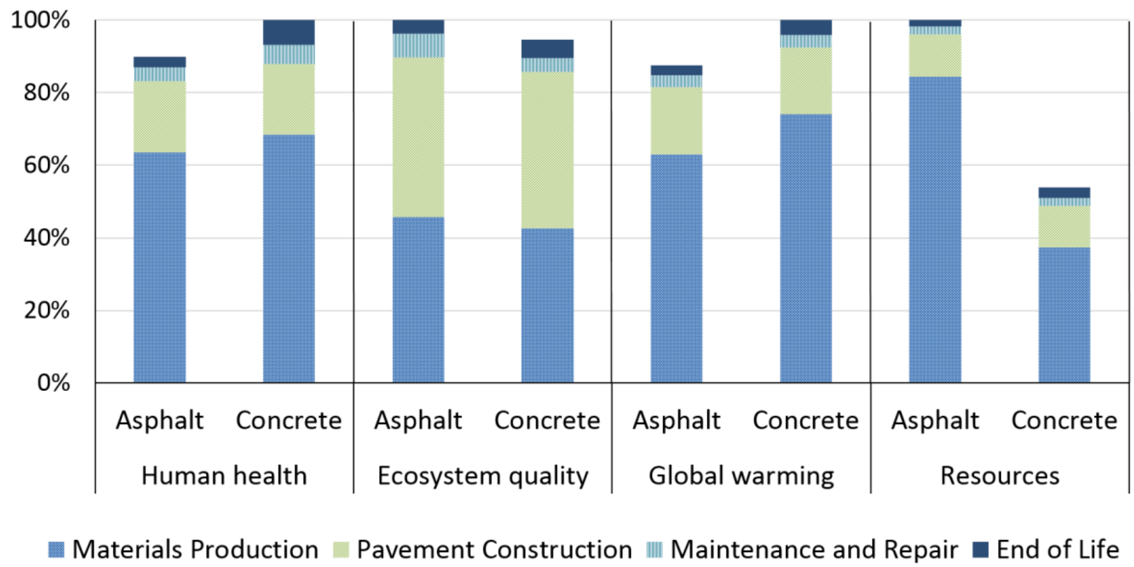

Figure 4.3. Endpoint results of concrete and asphalt scenario (IMPACT 2002+)

4.5.2 Results of uncertainty and variability analysis

Figure 4.4 shows the effect of uncertainty and variability of three different sources of allocation rules (4.4.a), variability in construction materials and methods (4.4.b), and parameters (4.4.c) in discrete and combined formats (4.4.d) on the midpoint results. The allocation choices can only alter the preferred scenario in four midpoint categories, as shown in Figure 4.4.a (aquatic acidification, aquatic eutrophication, terrestrial ecotoxicity, and aquatic ecotoxicity). These impacts are primarily driven by the crude oil supply chain, except for aquatic acidification (Table 4.2). The aquatic acidification results for asphalt and concrete are almost identical, and therefore, a slight variation can change the preferred scenario.

Despite propagating the sources of uncertainty mentioned above and the variability in the pair-wise analysis, the conclusion remains nearly steady in seven midpoint categories (confidence of greater than 80% on the preferred scenario). Significant differences are observed in the environmental impacts of the pavement scenarios in mineral extraction, non-renewable energy, respiratory organics, ozone layer depletion, land occupation, carcinogenic and ionizing radiation, which lead to confidence in the selection of the preferred scenario (Figure 4.4.d). According to Figure 4.2, in these impact categories, the difference between the asphalt and concrete results is greater than 30%, except for land occupation and carcinogenic effects. As shown in Figure 4.4.a, b, and c, the preferred scenario is minimally influenced by land occupation and carcinogenic effects because none of the uncertainty sources can individually influence the confidence of the results. The land occupation category is dominated by the infrastructures of processes in the background. Therefore, the variation of construction materials and methods and their corresponding environmental exchanges in the foreground do not have an effect on the results of this impact category. Furthermore, parameter uncertainty cannot change the preferred scenario in land occupation due to the high confidence in the traffic and road network, and allocation rules cannot do so due to the limited effect on crude oil and limestone powder production. The same rationale applies to the carcinogenic results. A case study in the same geographical context was performed using pair-wise uncertainty analysis at the midpoint level. The results showed a negligible degree of uncertainty in all midpoint categories except for aquatic eutrophication and carcinogenic effect (the indicator scores appear to be most certain for the remainder of the midpoint categories in 85-100% of the iterations) [3]. However, we note that this analysis did not consider the uncertainty due to variability in the materials and methods or the uncertainty of the allocation rule. Therefore, the study included a single source of uncertainty related to the data quality defined by the pedigree matrix in the ecoinvent v.2.2 as opposed to the ecoinvent v.3.2 used in this study.

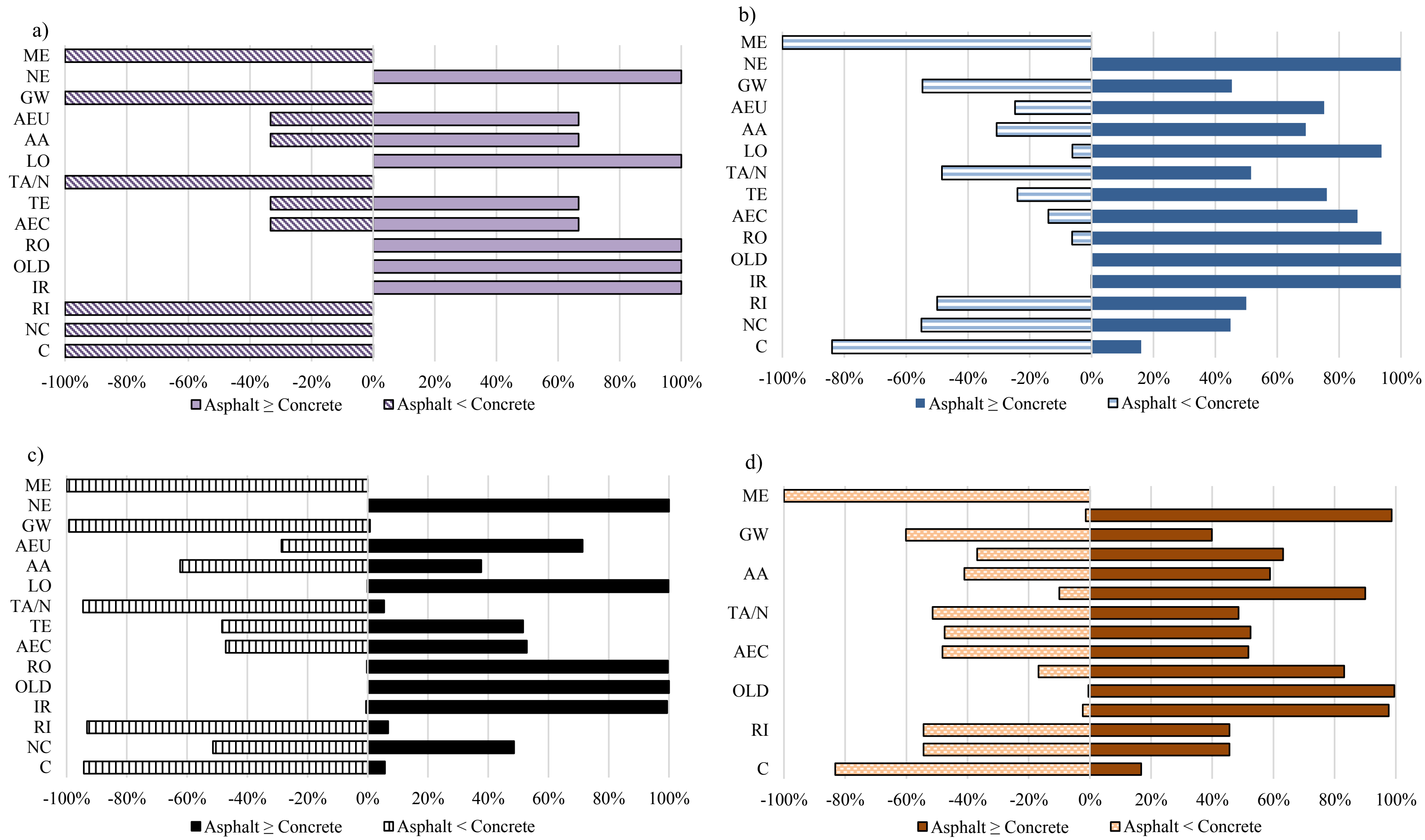

Figure 4.4. Analysis of a) scenario uncertainty (allocation choices), b) variability for the construction materials and methods, c) parameter uncertainty (data quality of environmental flows), and d) aggregation of three sources using Monte Carlo simulation with a 95 % confidence interval considering impact categories of IMPACT 2002+

Figure 4.5 shows the pair-wise uncertainty and variability analyses of the endpoint results. The uncertainty due to the allocation method can only change the results of ecosystem quality. Because of the change in the allocation method of bitumen, a change occurs in the inputs of the supply chain of crude oil extraction. A lower amount of crude oil is assigned to the corresponding unit process in economically allocated bitumen compared with the mass allocation (390 kg versus 1000 kg). According to Table 4.2, the terrestrial ecotoxicity, which primarily contributes to the ecosystem quality, is dominated by crude oil extraction (21% contribution). However, the difference between the ecosystem results for asphalt and concrete is less than 5%, and therefore, the conclusion is changed because of propagation of this uncertainty. In the resources endpoint category, according to Figure A2.10 in the Supplementary Information and based on the relatively significant feedstock energy of bitumen, the difference between the results of the asphalt and the concrete scenarios is large, and thus different methods of allocation do not lead to a change in the preferred scenario.

Variability of the construction materials and methods influences the environmental impacts of the pavement in two ways. The environmental impacts derived from the contribution of different materials and methods directly affect the changes in the results. In addition, the quality of pavement construction depends on the materials and the efficiency of equipment. Therefore, the pavement lifetime as well as maintenance and repair are changed and can be considered as indirect effects of the construction materials and methods selection. All of these indirect and direct effects are considered in this analysis. Unlike the uncertainty propagated by the selection of allocation method, the possible variations in construction materials and methods can cause changes in the preferred scenario for the climate change and human health categories, which shows how the selection of different alternatives and errors in pavement construction can simply change the conclusion of the comparative study. Key parameters (i.e., the parameters that link the reference flows to FU) significantly influence the outcome of impact assessment [186], and the change in the pavement lifetime (i.e., the key parameter in pavement LCA) shows a possible reversal of the preferred scenario in climate change and human health. This observation is neglected in certain similar pavement LCAs, whereas in other civil engineering studies, a sensitivity analysis on a single building shows significant changes in the results of global warming, acidification, energy, eutrophication, and smog categories considering variations in the building lifetime [176].

The parameter uncertainty defined by the pedigree matrix induces significant uncertainty in the ecosystem quality results. As the key contributor to the ecosystem quality impact (see Figure A2.9 in Supplementary Information), terrestrial ecotoxicity is the only midpoint category that has the largest relative uncertainty between the midpoints connecting to the ecosystem quality. The qualitative scores given to the main contributors of terrestrial ecotoxicity are relatively the worst for the geographical uncertainty indicator (Parameter Z_4 in Eq. 4.3). For example, according to Table 4.2, zinc emitted to the soil has the greatest contribution to the terrestrial ecotoxicity category for both scenarios. A geographical uncertainty score of four in tire wear emissions, as well as a basic uncertainty factor of 1.50, is assigned to this element and other heavy metals emitted to the soil [187]. As a result, coefficients of variation (CV) of 384% and 382% are calculated for terrestrial ecotoxicity of the asphalt and concrete, respectively. Current knowledge of ecotoxicity categories suffers from model and parameter uncertainty. One should note that the parameter uncertainty in the pedigree matrix can only consider the quality of the value used to quantify the elementary flows (i.e., inventory) that contribute to impacts on indicators such as ecosystem quality. The same order of uncertainty (CV of 327% and 313% for asphalt and concrete, respectively) occurs in non-carcinogenic effects due to the significant contribution of zinc in this category. However, the contribution of this midpoint category is small in human health results (4% according to Figure A2.9) and therefore cannot impose a significant change in the preferred scenario. In addition, the 10% difference between the results for asphalt and concrete in this category leads to more confident decision-making on the preferred scenario compared with ecosystem quality.

The combined effect of variability sources, methodological choices, and parameters leads to a degree of uncertainty and a more uncertain conclusion. The difference between the base-case results of the asphalt and concrete scenarios and the degree of uncertainty induced by different sources both influence the change in the conclusion of comparative studies. In the case of ecosystem quality, the results are dominated by scenario and parameter uncertainties. Therefore, more reliable data (obtained by avoiding the use of a similar process to match the considered process or by simply using a similar process as a proxy and using an updated onsite-measured data source obtained from many samples) are required to reach a less uncertain conclusion. Although the variability of construction materials has a major influence on the global warming and human health categories, certain differences are identified between construction equipment efficiency and scenarios. These results indicate that using practical construction equipment efficiencies and realistic construction materials are more important than improving the quality of the upstream data for estimation of the human health and global warming effects of pavement alternatives. Considering the small change in the probability of combined results in ionizing radiation or respiratory inorganics (Figure 4.4.d), it appears that the variability sources have the greatest effect on the outcome of these categories. To ensure the contribution of each source, a global sensitivity analysis on the uncertainty results is proposed for further research.

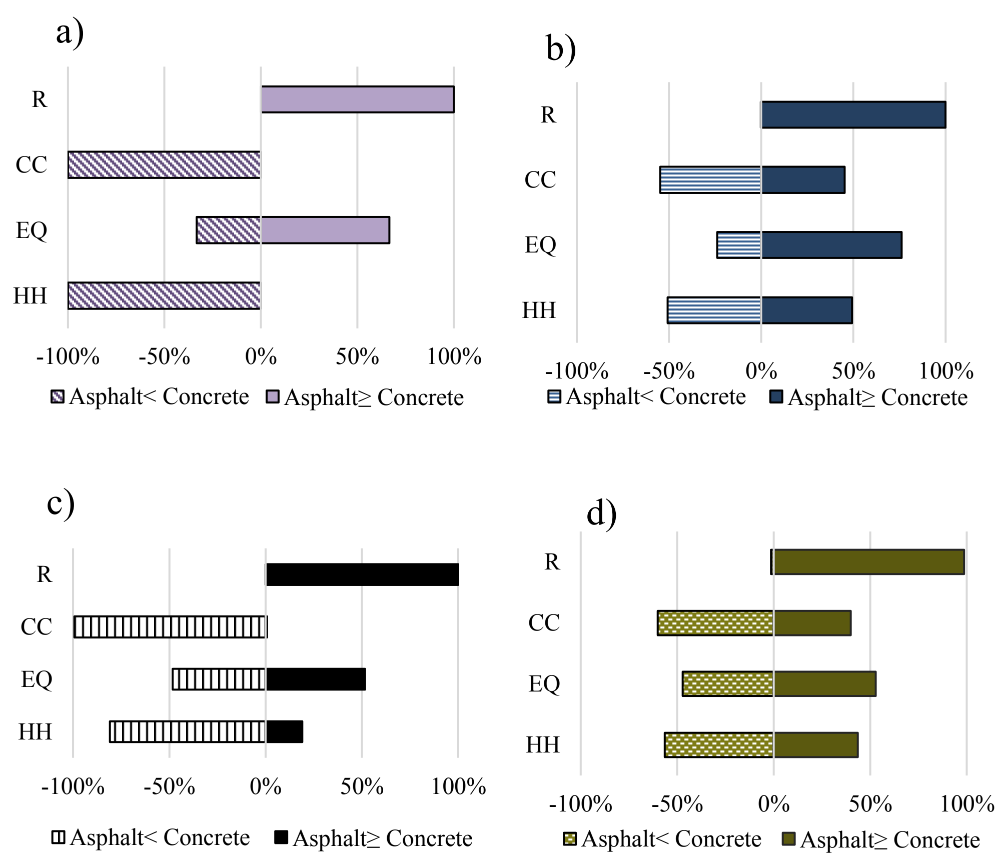

Figure 4.5. Analysis of a) scenario uncertainty (allocation choices), b) variability for the construction materials and methods, c) parameter uncertainty (data quality of environmental flows), and d) aggregation of three sources using Monte Carlo simulation with a 95 % confidence interval considering IMPACT 2002+ damage categories

4.6 Conclusions and outlook

This study proposed a straightforward method to address the individual and combined effects of uncertainty and variability. To attain the paper's objective, an LCA of two pavement alternatives was performed to identify the preferable alternative for the province of Quebec, Canada from an environmental perspective. The proposed method simply analyzes the individual and combined effects of common uncertainty and variability sources on different life cycle stages of the pavement. Without considering such uncertainty and variability, the results show that the concrete scenario has a slightly lower impact than that of asphalt in the eight impact categories. Asphalt has a slightly lower impact on the human health and global warming damage categories than concrete. The probabilistic approach results show that uncertainty due to allocation choices influences the preferred scenario for ecosystem quality. Furthermore, the conclusion reached on the preferred scenario in the global warming and human health results is subject to variation in the iterations.

In almost half of the iterations, each alternative possesses lower impacts than the other one due to the possible variation in construction materials and methods. In contrast, the parameter uncertainty induced by the pedigree matrix shows only relative uncertainty in the selection of the preferred scenario for ecosystem quality. Therefore, disregarding one of these uncertainty and variability sources can jeopardize the ability to reach a less certain conclusion in the endpoint categories. Despite propagating the sources of uncertainty mentioned above and the variability in the pair-wise analysis, the conclusion remains nearly steady in seven midpoint categories (confidence of greater than 80% on the preferred scenario). Significant differences are observed in the environmental impacts of the pavement scenarios in mineral extraction, non-renewable energy, respiratory organics, ozone layer depletion, land occupation, carcinogenic and ionizing radiation, which lead to confidence in the selection of the preferred scenario.

A minimum 30% difference between the asphalt and concrete midpoint results appears to be the interval over which the addressed sources cannot change the conclusion related to the eco-friendly alternative. Indeed, the environmental burdens of the pavement scenarios are sufficiently distinct to present the preferred scenario for mineral extraction, non-renewable energy, respiratory organics, ozone layer depletion, land occupation, and ionizing radiation.

Further experimental studies are required to characterize the emissions when de-icing salt removed through traffic spray processes and particulates suspended in the air after pavement surface drying are considered in the assessment. Variability sources in the background processes (e.g., the source of raw materials and bitumen) reveals a new outlook for the results. In addition, contribution analyses for each source and examination of other types of distribution for variability sources are interesting topics for further research studies. Other processes attributed to the use stage of pavements, such as pavement fuel consumption, albedo effect, lighting energy, and generated noise (i.e., processes that are not directly connected to reference flows) can be added to the model in the pertinent LCA framework to broaden the system boundary and offer full-scale decision-making. Such a model can be provided through the development of a dynamic consequential framework. As shown in Figure A2.11 in appendix 2, the application of a consequential framework to this case study resulted in a change in seven out of 15 impact categories. Further investigation should be oriented to the development of a dynamic consequential framework to investigate the conclusion made for policy-making decisions on pavements. Finally, the model uncertainty induced by characterization factors can be incorporated in future uses of the applied methodology.

CHAPTER 5 REMOVING SHADOWS FROM CONSEQUENTIAL LCA THROUGH A TIME-DEPENDENT MODELING APPROACH: POLICY-MAKING IN ROAD PAVEMENT SECTOR

Avant-propos

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Titre français: Éliminer les ombres de l'ACV conséquentielle grâce à une approche de modélisation dynamique: l'élaboration de politiques dans le secteur de routière.

Contribution au document: Présenter la méthode développée pour évaluer les impacts conséquents dynamiques des alternatives de chaussées d'un point de vue politique.

Résumé français

L'absence de considération de l'aspect dynamique dans l'analyse du cycle de vie conséquentielle (ACVC) limite la compréhension des décideurs des flux d'émissions au fil du temps. Dans cette étude, nous proposons un cadre méthodologique dynamique d'ACVC pour évaluer les conséquences environnementales des chaussées. Les changements dynamiques dans les matrices du vecteur de la demande et de la technosphère ont été calculés en utilisant une échelle temporelle pertinente pour les technologies d'approvisionnement affectées et en incorporant des paramètres dépendant du temps. Une simulation de Monte Carlo a ensuite été menée pour propager la variabilité, l'incertitude du modèle et les sources d'incertitude des paramètres aux résultats de dommages. Les résultats montrent que la simplification d'une ACVC des chaussées en négligeant les changements en temps réel entraîne des variations notables dans les résultats des dommages. Les avantages environnementaux de la substitution de l'asphalte par du béton sont sous-estimés de 7, 17 et 77% pour les catégories de changement climatique, de la santé humaine et des ressources, respectivement. Une surestimation de 114% a également été observée dans la catégorie « Qualité des écosystèmes » lors de l'utilisation du cadre statique. De plus, l'absence de prise en compte d'un profil temporel des émissions de gaz à effet de serre, en utilisant des facteurs de caractérisation statiques, conduit à une surestimation des bénéfices de la substitution de l'asphalte par du béton au niveau du potentiel de réchauffement planétaire de 473,5 tonnes CO_{2eq} (105%). Les résultats de l'analyse de l'incertitude montrent que la contribution de la variance dans les catégories de dommages de 41 à 71% est principalement attribuée à la comptabilité mensuelle de la température et à la durée de vie.

Mots-clés : Analyse du cycle de vie conséquentielle; Incertitude et variabilité; Inventaire dynamique; Effets indirects; Sélection de la chaussée; Politique environnementale.

5.1 Abstract

A lack of dynamic accounting in consequential life cycle assessment (CLCA) can keep policy-makers from having an accurate analysis of emission flows over time. In this study, we propose a dynamic CLCA framework to assess the environmental consequences of pavements. Dynamic changes in the demand vector and technosphere matrices were computed using relevant time horizons of affected supply technologies and incorporating time-dependent parameters. A Monte Carlo simulation was then conducted to propagate the variability, model uncertainty, and parameter uncertainty sources of life cycle inventory to the damage results. The results show that simplifying the pavement CLCA framework through neglecting dynamic changes results in notable diversions in the damage results. The environmental benefits of substituting asphalt with concrete are underestimated by 7, 17, and 77% for climate change, human health and resources categories, respectively. A divergence of 114% was also observed in ecosystem quality when using the static framework. Moreover, the lack of accounting for a temporal profile for GHG emissions using static characterization factors leads to an overestimation of the GWP benefits of substituting asphalt with concrete of 473.5 metric tons CO_{2eq} (105%). The uncertainty results show 41-71% contribution of the variance in the damage categories is caused by the variability sources and is primarily attributed to monthly temperature accounting and service life.

Keywords: Consequential life cycle assessment; Uncertainty and variability; Dynamic inventory; Indirect effects; Pavement selection; Environmental policy-making.

5.2 Introduction

Pavement infrastructures, as pre-requisites for sustained economic development, play important roles in growth and connecting people in different regions. Governments are working to reduce the environmental impacts of transportation enabled by these pavements. Road transportation is the largest contributor to greenhouse gas (GHG) emissions in various geographical contexts [162]. To curb these GHG emissions, governments have adopted fuel efficiency standards and regulations but the subject of pavement selection has not yet been fully considered. The environmental impacts of pavement are not limited to the materials and machinery of construction (see e.g., [188] and [189]). Pavement characteristics can induce major changes in fuel consumption of the vehicles [160]. Thus, pavement selection can be considered an important part of the strategy to reduce the environmental impacts of road transportation. Beyond road transportation, pavement selection can also affect energy consumption in buildings, particularly in urban zones, by radiative forcing (RF) on ambient temperatures. This influence on temperature leads to changes in electricity consumption, as climate control systems compensate for heat gain or loss in buildings [8].

The temporal distribution of impacts over the pavement life cycle is not fully captured in previous studies. Neglecting changes which occur over time can manifest in the results in two ways:

1. The improvement in efficiency of fuel consumption and emission factors are disregarded.
2. Considering the long use-phase of pavements, a number of parameters change as a function of time and use. Oversimplification in trying to capture these dynamic changes in parameters may result in inaccurate estimation of the environmental impacts during the use phase.

Additional fuel consumption by vehicles is linked to increasing pavement surface roughness over the life cycle. Surface roughness after initial construction is considered the base value for roughness. Emissions based on fuel consumption are calculated over time based on a progressive increase from that initial roughness. It is useful to analyze the dynamic fuel consumption of vehicles between various pavement alternatives in comparative studies. The RF effect of albedo is generally calculated as the RF difference between the pavement reflectivity and reflectivity of a fully reflective surface [162]. Given that all the life cycle phases are considered in a relative format, it is coherent to quantify all the burdens based on the same base case to attain a sensible and valid contribution analysis of the phases in the impact categories.

Generally, in consequential life cycle assessment (CLCA) framework, an alternative (ALT) case will replace a base case, namely, a business-as-usual (BAU) scenario. Therefore, the BAU case seems to be a consistent baseline for all time-dependent parameters in the life cycle phases of pavements. Pavement-related changes in energy consumption can have indirect effects on the fuel market and consumer behavior. These effects can be captured, to some degree, by consequential life cycle assessment (CLCA) [190]. Moreover, conducting an LCA using a consequential framework prevents isolation of a product system from the rest of the technosphere within an economic framework [191]. CLCA frameworks can consider consequences of decisions through system expansion, which is beyond the defined system boundaries, i.e., in the parts of multifunctional processes that have been allocated or simplified through averaging.

Various methods have been proposed to conduct a CLCA. One common assumption in these methods is the consideration of a single time-horizon in affected technologies. In fact, the affected technologies are intended to be valid for long time periods and typically involve long-term suppliers. This assumption is usually justified. When a long-term change is planned and announced well in advance of implementation, it produces only long-term effects, i.e., the effects from installation and production on newly installed capacity [192]. This may be the case in the maintenance of infrastructure, for example, where decision-makers can predict the work schedules well before new construction. The other justification for isolating the long-term effects of a change is that accumulation of individual demands results in capacity adjustments as a continuous process. This continuous process is a basis for decisions on the provision of capital investment. This justification for simplifying the change effect may not be applicable to the CLCA of products with long service life, such as in pavements. Short-term changes in demand of intermediate flows in initial phases of the life cycle, e.g., materials for construction of infrastructures, are of limited duration and will be terminated as soon as interventions in this phase are finished. Therefore, decision-makers may not need to procure a continuous production volume for a regulated shape of demand. Second, in constructing infrastructure, the market conditions for intermediate flows used in initial phases of the life cycle have little influence on capacity adjustments since the production capacity is significant and the capital cycle of infrastructures is long [193]. In a review paper, Zamagni et al. addressed this time-constant consideration of the affected technologies in the storyline of a product system as a "shadow" on the CLCA concept [36]. In fact, by isolating long-term impacts in CLCA of pavements, the results tend to obscure short-term impacts. In addition, using a single time horizon demonstrates only one perspective of the life cycle assessment (LCA) results possibly introducing inadvertent bias and inconsistency into the outcomes. For example, exclusion of short-term effects may result in other overlooked impacts from the short run product system, although the frontier between short and long-term is still in debate [33]. The result of evaluating affected suppliers with different time-horizons is referred to as "complex marginal supplier" and takes into account the evolution to changed state from the baseline [164].

Another argument against static analysis, not specific to CLCA but also relating to other LCA frameworks, is that the impacts of emissions are merely the arithmetic sum of all the current and future activities. For example, in calculating global warming potential (GWP), the severity of the emissions depends on the GHG type, quantity and timing of the induced GHGs [163, 194]. To assess environmental impacts through dynamic characterization factors (CFs), a dynamic life cycle inventory (DLCI) is required as the dynamic accounting of the environmental impacts can produce significant relative differences across product systems. In addition, the dynamic assessment of impacts, such as GWP, can prompt large absolute differences compared to static GWPs calculated against arbitrary time horizons. An example of attributional LCA of pavement construction can be found in [56, 151] that a 66% difference in the GWP impacts was observed between dynamic and static 100-year GWP results. Unlike the previous steady-state inventory, the use of a consequential DLCI can facilitate the goal of reaching an incremental accuracy of LCA results by integrating dynamic CFs. In this study, we aim to develop a dynamic consequential life cycle inventory for assessing the potential impacts of pavements substitution.

We established a consistent approach to investigate and compare the impacts of a decision by investigating market reactions to the changes in product demand occurring through the pavement life cycle. Changes in demand were linked to the time-dependent technosphere and the ecosphere matrices to generate the inventory. Finally, the DLCI results were assigned to dynamic and static CFs of endpoint categories to assess damage to the environment.

5.3 Methodology

5.3.1 Description of the dynamic consequential model for pavements

We used the basic equation for calculation of the inventory matrix of a process-based LCA [195] to simplify the dynamic aspect of the CLCA framework, where the BAU scenario substitutes with the ALT scenario comprising the same level of functionality as Eq. (5.1):

$$\Delta \mathrm{LCI}(\mathrm{t}) = \sum_{\mathrm{i}} \Delta \mathrm{LCI}_{\mathrm{i}}(\mathrm{t}) = \sum_{\mathrm{i}} \mathrm{B}(\mathrm{t}).\,(\mathrm{A}(\mathrm{t}))^{-1}.\,\Delta \mathrm{f}_{\mathrm{i}}(\mathrm{t}) \qquad (5.1)$$

where ΔLCI(t) represents the life cycle inventory matrix at time t and for life cycle component i; Δf(t) a vector that represents the changes in demand due to substituting BAU with ALT at time t; A is the technosphere matrix representing the input intermediate flows required for delivering a unit of process outputs; and B represents the biosphere matrix incorporating the environmental interventions required for each intermediate flow. The dots in this equation represent matrix products. The elements of the biosphere matrix can change in time due to the implementation of emission control systems and regulations, which are well explained in previous research works [196]. However, the focus of this study is on the dynamic aspect of consequential inventory that is well reflected in the technosphere matrix. Changes in the technosphere matrix over time have to do with intermediate flows modifications and technology efficiency improvements. In this study, we computed the value of A(t) according to Eq. (5.2):

$$\mathrm{A}(\mathrm{t}) = (\mathrm{A}_{\mathrm{base}} \circ [\mathrm{T}(\mathrm{t}) + \mathrm{R}(\mathrm{t})])_{j} \qquad (5.2)$$

The ∘ in Eq. (2) represents a Hadamard product, i.e., an entrywise multiplication of matrices. In addition, A_{base} represents the quantity of intermediate flows required to fulfill the processes in the first year of service life; and T(t) modifies the quantity A_{base} for the technical efficiency in time. j stands for the short-term or long-term demand for a specific intermediate flow. We defined parameter T_{shift} as the number of years after beginning the life cycle when change in demand will affect new capacity installation. If $t \geq T_{shift}$, the long-term affected supplier is affected by the demand change through the new capacity installation, while prior to reaching T_{shift}, the current flexible suppliers will be affected, i.e. the short-term affected supplier. The short and long-term affected suppliers will be identified based on the operating costs, and the market will adjust its capacity to cover the demand. In the T(t) matrices, each element $a_{i,p}(t)$ represents the efficiency improvement for the product i to the processes p at time t and is calculated according to Eq. (5.3). For example, fuel efficiency of passenger cars and trucks tends to improve over time as reported by the government [197].

$$\mathrm{a_{i,p}(t)} = 1 - [\frac{\partial E}{E}(t)]_{\mathrm{i,p}} \qquad (5.3)$$

Where $\frac{\partial E}{E}(t)$ represents the relative change in the technology efficiency. The elements of T(t) can hold any values more than 0, e.g., it can fall between 0 and 1 (when $\frac{\partial E}{E} \geq 0$) in case of improvement in fuel consumption of vehicles or can be more than 1 (when $\frac{\partial E}{E} < 0$) for output flows of a resource extraction process. To consider the consumer reaction to the improvement in fuel efficiency, a time-dependent rebound effect R(t) is included in Eq. (5.2) that modifies the values of T(t) matrix. For example, as fuel efficiency improves, drivers usually counterbalance a percentage of this improvement by purchasing more fuel [198]. The elasticity of technology efficiency (η_E) is implemented to offset a proportion of the improvement in the technology efficiency. The procedure of calculating the elasticity efficiency is presented in section 4.1.1 of the SI.

Each element of $b_{i,p}$, in the R(t) matrix is calculated as:

$$b_{i,p} = [\frac{\partial E}{E}(t) \times \eta_E(t)]_{i,p} \qquad (5.4)$$

Where $\eta_E(t)$ represents the efficiency elasticity corresponding to product i. The R(t) matrices have the same dimension of T(t) and A_{base}.

To compute the value of $\Delta f_i(t)$, we consider the avoided and additional demands from the BAU and ALT scenarios. Therefore, for a given time t, we have:

$$\Delta f_i(t) = \int_{t-1}^{t}([\Delta f_i(t)]_{ALT} - [\Delta f_i(t)]_{BAU})dt \qquad (5.5)$$

After calculating the DLCI, dynamic LCA results can be generated by assigning the proper dynamic characterization factors (CFs) to the time-dependent inventory.

5.3.2 Description of the Case Study

The purpose of this study is to evaluate the environmental consequences of reconstruction of existing pavement infrastructure. We chose a case study where asphalt pavement (BAU scenario) was substituted with jointed plain concrete pavement (ALT scenario) to apply the proposed method. In this study, the functional unit was defined as "providing a path for traffic service over the entire network of the two-lane roads with 20,000±1,000 AADT, including 5% of trucks, in the province of Quebec, for a 50-year lifespan". We determined relevant time horizons for technologies affected by demand changes during the pavement life cycle according to life cycle phases. Figure 5.1 summarizes the connections between short-term and long-term affected technologies with each life cycle component. Connections include materials, construction, IRI-induced and rigidity-induced fuel consumption, albedo effects [in terms of radiative forcing (RF) and urban heat island (UHI)], lighting, and carbonation i.e., the ability of concrete to reabsorb CO_2 through a chemical process [156](readers are referred to page 197 in Appendix 3 to get more information about the carbonation calculation and effective parameters). It should be noted that some components incorporate both the short-term and long-term effects during the use phase of the pavement since their demands are changing during both periods. In addition, we considered the effects of carbonation and RF by adjusting the CO_2 balance of the system. Thus, the carbon flows were added directly to inventory results. More information justifying time horizon assignments for the affected flows to each life cycle phase is provided in Appendix 3. We also used the ecoinvent consequential database v.3.2 for modeling background processes [178].

In much of the transportation literature a period of 5–10 year is estimated empirically for short-term effects [199]. However, we utilized a sensitivity analysis to assess the effects of the frontier between long-term and short-term horizons. Certain parameters, such as monthly ambient temperature and downward solar radiation at the surface of the Earth, induce significant variations in the inventory results during a year [128]. Hence, a monthly time step was considered to produce the dynamic inventory. In the next step we identified affected technologies and the determining products in case of a multi-functional process for different time horizons using the step-wise procedure proposed by Weidema [200]. Readers can find details of the procedure for finding the affected technologies for each flow in the foreground system in Appendix 3. To calculate demand changes we used a set of dynamic parameters for each life cycle component. We also considered a one-year lag time for the procurement of materials through the supply chain. A comprehensive overview of the demand in BAU and ALT cases for materials production, construction, maintenance and repair (M&R) and end-of-life phases can be found in previous work [201]. In addition, a detailed description of the methodology for computing change in demands of use-phase components is presented in Appendix 3. Table 5.1 is provided to reflect the significance of the difference between the impacts of CLCA and ALCA flows. Readers are referred to Table A3.6 for a complete list of the affected suppliers.

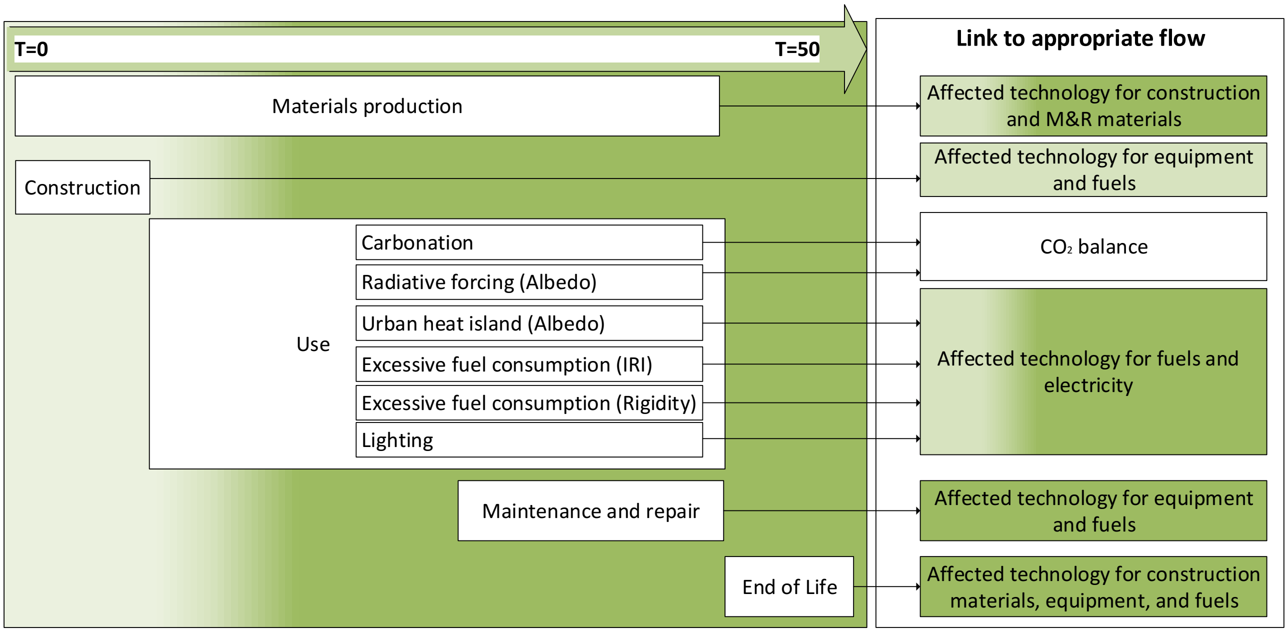

Figure 5.1. Connections between pavement life cycle components and affected technologies and flows with different time horizons.

Table 5.1. Summary of affected technologies in different time horizons (WCS = West Canadian Select, WTI = Western Texas Intermediate)

Intermediate flow (unit)	**Short-term affected supplier [1] (kg CO_2/Unit) [*]**	**Long-term affected supplier [1] (kg CO_2/Unit) [*]**	**Current average market [2] (kg CO_2/Unit) [*]**
Cement (t)	Dry kiln technology with natural gas (834)	Pre-calciner and pre-heater technology with forest biomass (515)	Average production of dry and pre-calciner technologies with various fuels (821)
Reinforcing rebars (t)	German manufactured with blast oxygen furnace technology (2998)	Canadian manufactured with blast furnace with carbon capture and storage and top gas recycling technology (1996)	Average of recycled and virgin steel input produced through convertor and electric arc technologies (2251)
Car transportation (km)	WCS crude oil (0.376)[3]	WTI crude oil (0.283)[3]	Average of imports from WCS, WTI, and OPEC (0.363)[4]
Bitumen (t)	WTI crude oil (624)[3]	Bioasphalt (92)[3]	Average of imports from WCS, WTI, and OPEC (322)[4]
Fuel for asphalt production (t)	Light fuel oil (27.1)[3]	Natural gas (24.2)[3]	Average of Light and heavy fuel, natural gas, biogas, and propane (28.5)[4]
Low voltage electricity (kWh)	Gas power plant import (0.447)	Wind farm (0.035)	Average of hydropower, wind, imports (0.025)

Consequential long-term dataset was used for background processes modeling.
[2] Attributional recycled-content dataset was used for background processes modeling.
[3] System expansion was applied to the multifunctional process.
[4] Economic allocation was applied to the multifunctional process.
[*] GWP100 characterization factors were used.

5.3.3 Impact assessment methods

We considered the damage categories ecosystem quality (EQ), human health (HH), and resources (R) using the CFs proposed in IMPACT 2002+ [202] to assess the significance of the potential damages of the substitution. Interpretation of these results does not require extensive knowledge of environmental effects, and the policy-maker would be able to easily make decisions. In addition, we used the CFs for global warming potential (GWP) with a 100-year time horizon proposed in an IPCC report [203] to analyze the climate change (CC) impact of the substitution. All CFs in IPCC and IMPACT 2002+ are constant in time. Nevertheless, the proposed dynamic framework enables one to link the inventory with a time-dependent impact assessment method. Therefore, we used dynamic CFs for GWP to evaluate the CC impact through time. Inspired by the approach proposed by Levasseur et al. [163], we assigned the dynamic GWP CFs to time-dependent LCIs obtained by linking the demand changes to the corresponding affected technologies as Eq. (5.6):

$$\mathrm{GWP(t)} = \sum_{k=0}^{t}[\Delta\mathrm{LCI(t-k)}\,.\,\mathrm{DCF(k)}] \qquad (5.6)$$

where GWP (t) is cumulative GHG emissions at year t, computed by summing instantaneous radiative forcing at any time t caused by all emissions from year 0 to year t (the relative starting time of the emissions is considered as 0 and all the GHG emissions during the year are assumed to be accumulated at the end of year and is assigned to the corresponding CF); k is number of years between 0 and t; and DCF stands for dynamic characterization factor for each GHG elementary flow. The dot in the equation represents the matrix product. It should be noted that, a marginal impact modeling in LCIA stage can be applied as the additional impact per additional unit emission or extraction induced by the product system on top of the existing background system [204]. This nonlinearity integration in LCIA stage allows decision-makers to resolve accuracy issues, such as considering nonlinearity of impacts based on local conditions like extremely high or low background concentrations to which the demand changes contribute an additional emission. Future work should explore the effects of non-linear LCIA on the consequential modeling.

5.3.4 Treatment of uncertainty and variability sources

Analyzing uncertainty and variability sources in LCA results allows one to evaluate and improve the robustness of the conclusions. We classified these sources into a) model uncertainty, the measurement error in physical constants or modeled relationships in the use–phase; b) data quality uncertainty, the parameter uncertainty related to quality of the inventory; and c) variability, the inherent variations in the parameters [165, 201]. We then conducted Monte Carlo simulations to propagate these sources to the four assessed categories using the Crystal Ball spreadsheet-based application. Analyzing combined effects of sources of uncertainty and variability provides a comprehensive perspective on the precision of the study. We evaluated the contribution of each source of variability and uncertainty, and its corresponding parameters, to the total uncertainty. This classification helps one to refine and prioritize uncertainty sources or parameters that have the most effect on variance. We computed the normalized squared Spearman rank correlation coefficients to characterize the relative contribution of each input in the variance of the damage categories. The information about the parameters and procedure of uncertainty analysis is explicitly presented in Appendix 3 and 4. Mutel et al. proposed to set the number of Monte Carlo iterations 100 times the number of assessed parameters in order to minimize the uncorrelated errors in the results of contribution to variance, i.e. the Spearman rank correlation coefficient [205]. The variation of results associated with uncertainty and variability sources in input data was assessed with 200,000 Monte Carlo iterations. Justifications for quantifying characterizations of uncertainty and variability sources are presented in Appendix 3.

5.4 Results and discussions

5.4.1 Dynamic human health, ecosystem quality and resources results

Figure 5.2 shows cumulative, dynamic and static results of the three damage categories representing the difference between the BAU and ALT scenarios. Therefore, it is possible for the results to be either positive (when ALT has a larger impact than BAU) and vice versa. For ease of comparison with other studies, we normalized the results to 1-km of pavement. A dynamic CLCA approach helps to provide a more comprehensive estimate but is always limited by the understanding of model practitioner of the pavement system, as well as the model simplifications and assumptions. Therefore, it is important to understand the influence of key dynamic factors on the variables in the model rather than to compute the absolute values for the variables. We observed an increase in environmental damages at the beginning of the life cycle, which coincides with the material production and construction phases in all the damage categories except for R (Figure 5.2 and 3). The EQ, HH, and CC impacts of producing concrete are greater than those for asphalt, while the feedstock energy embodied in crude oil (51.2 MJ/kg) leads to a higher resource consumption impact than the ALT scenario in the early ages.

The difference between the environmental damages of two pavement systems for the first 15 years is relatively small compared to that for the later ages. As we go further in the life cycle, we find larger negative impacts implying an increase in the environmental benefits obtained by substituting the BAU with the ALT scenario. Sharp decreases at the ages of 15 and 28 years are related to the avoided demand for M&R of materials and machinery for the BAU case when a new overlay system will replace an old one. As these M&R schedules occur in the long-term, the long-term asphalt suppliers of the M&R of materials are affected by the decrease in demand. For ecosystem quality, the sharp decreases are more significant than those in other categories since 208 mg aluminum and 16.7 mg zinc are emitted by 1-kg wood ash landfarming, resulting in 2.073 PDF.m^2.yr per kg bioasphalt (i.e., the long-term affected technology for bitumen production). Comparing with Steele et al. [206], these toxicity emissions were not observed since they used the TRACI v.2 method that does not capture terrestrial emissions for aluminum [207]. To study the significance of the M&R schedule, we incorporated a sensitivity analysis of the repair intervals (Table A3.1 in Appendix 3). Results showed less than 5% change in the R and EQ damage differences and approximately 10% difference in HH and CC when each interval is postponed or hurried for two years (Figure A3.31 in Appendix 3).

While the materials production predominantly affects EQ results, the use phase and, particularly, excessive fuel consumption due to pavement rigidity induce the major differences between the damages in the BAU and ALT scenarios (Figure A.3.26 in Appendix 3). Rigidity is ten times greater in the ALT case compared to BAU on the one hand, and induced crude oil extraction and petroleum consumption by vehicle fuel demand, on the other hand, resulted in a significant contribution by rigidity induced fuel consumption. The structural resistance of the surface layer to distresses, i.e. the modulus of elasticity, is ten times greater in the ALT case compared to the BAU. Therefore, the induced crude oil extraction and petroleum consumption by the change in vehicle fuel demand are altered by the distinction between the two scenarios.

It should be noted that the IRI induced fuel consumption is constantly changing as a function of both the pavement use and in M&R repair and at certain ages (e.g., between 28-32-year ages). Hence, we observed an increase in IRI-induced fuel consumption when substituting the BAU with ALT which offset a part of the environmental credits obtained by the substitution. Fuel consumption due to rigidity follows a steady increase, as shown in Figure A3.22-A.3.25 in Appendix 3, and depended only on the monthly temperature. Despite resurfacing the ALT scenario with asphalt materials at age 40, the rigidity of the ALT scenario, as the surface layer from 0-40 years and as a base from 40-50 years, reduces the fuel consumption throughout the pavement life cycle. However, after resurfacing the ALT with asphalt materials at the age of 40, other use phase components such as albedo effect, IRI effect, and carbonation that depend on the surface characteristics of pavements, produced similar damage values. Therefore, there are no changes in the demands of the flows for these use-phase components.

Another parameter that contributes significantly to the difference between BAU and ALT results is the electricity consumption related to the urban heat island (UHI) effect. Peng et al. reported that the effect of UHI is more intense in summer than winter due to lower solar intensity during winter [8]. In another study, Kolokotroni et al. reported the decrease in heating demand in winter can offset the cooling demand induced by UHI effect in London, leading to 90% and 50% reduction in electricity consumption in short and long-term, respectively [208]. In this case study, 61% of the whole length of the road with the specified traffic service is considered as UHI effective fraction of the pavement in urban neighborhood [209]. In our case, incorporating heating and cooling demand changes due to the UHI effect in long and severe winters and mild summers, such as those prevailing in Quebec, Canada, results in a net increase in electricity demand (46±9 MWh/yr/km pavement). At least 75% of the UHI-induced emissions in the four damage categories took place during the short-term period and were caused by increases in electricity production in a gas power plant in the U.S. (i.e., the short-term affected supplier for electricity). The monthly air temperature plays a significant role in UHI-induced electricity consumption. Therefore, we examined the effect of temperature variability in the geographical context of the case study and included this effect in the statistical results. In addition, as a simplification, we considered heterogeneous urban neighborhoods to be uniformly distributed buildings of equal story and size with a constant household number. In future work, to approach the reality of an urban neighborhood, actual geometry conditions will be used to increase the accuracy of the model through geographic information systems.

The endpoint results computed by the DLCI presented in Figure 5.2 and 5.3 give us a clear perspective of life cycle emissions and consumptions. These results also help us to understand how changes in certain elements of the system boundaries influence both other elements and the pavement supply chain as a whole. Calculating the emissions with a static LCI provided us divergent results. As shown in Figure A3.29, using a single long-term affected technology for each unit process leads to an underestimation in the environmental benefits of substituting BAU with ALT in the CC, HH, and R categories. While in EQ, we found that singling out the long-term affected technology and ignoring the dynamic aspect of the time-dependent parameters can increase the environmental benefits of the BAU-ALT substitution by 114% compared with the dynamic results. However, the existing variation due to the uncertainty and variability sources in static results and might make the differences among the dynamic and static results not statistically significant and can merit a further investigation for future research.

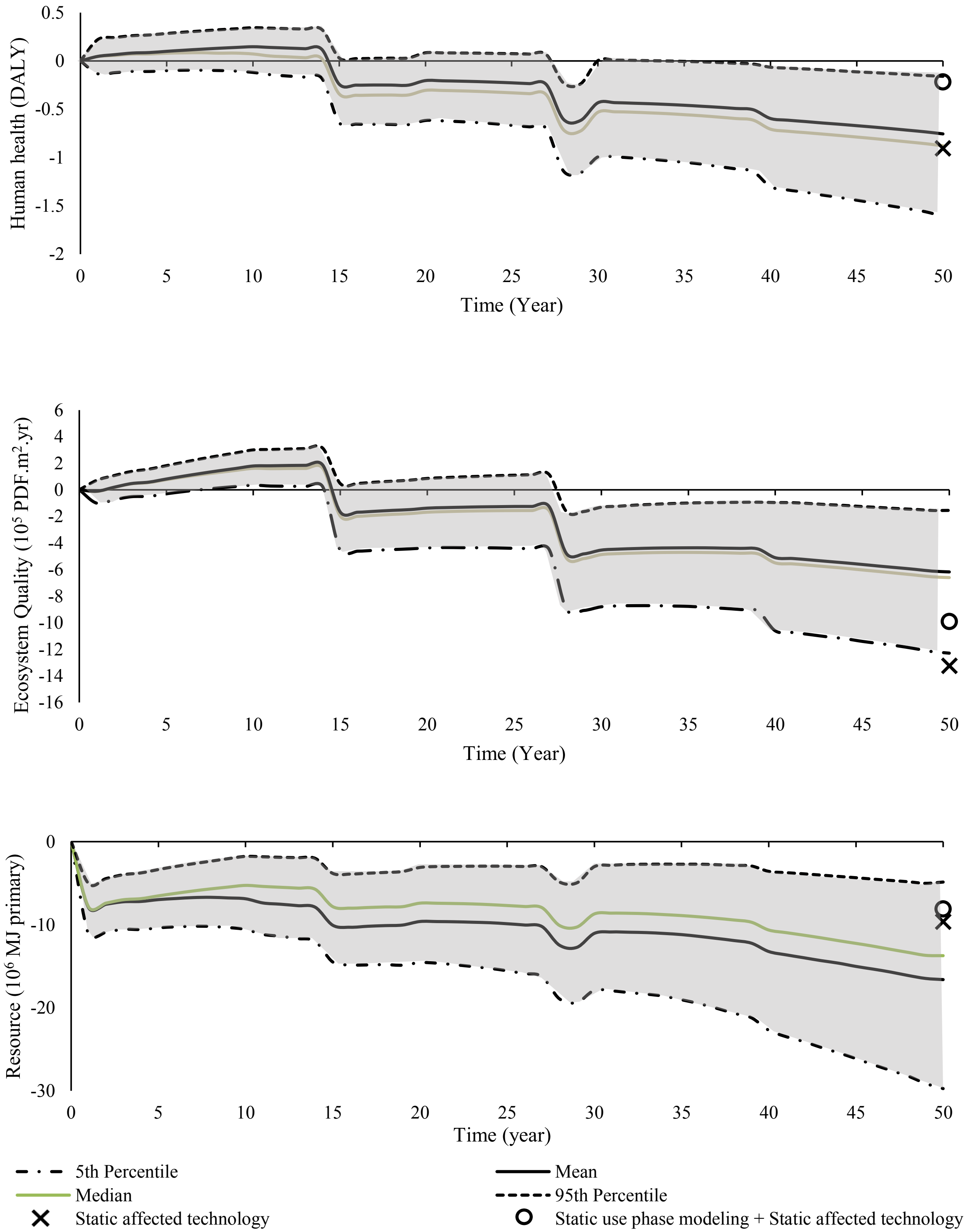

Figure 5.2. Accumulated mean, median and 5th and 95th percentile results of ecosystem quality (EQ), human health (HH), and resources (R) based on IMPACT 2002+ LCIA method.

Static characterization factors were used for all the scenarios. In the static affected technology scenario, we used a similar modeling framework to that of the dynamic except that we only linked demand to long-term affected technologies. In static use phase modeling with static affected technology, in addition to isolating the affected supplier of long-term technology, we modeled the use-phase with static inputs. A list of input parameters is available in Appendix 4 tables and Table A3.1 in Appendix 3).

5.4.2 Dynamic vs. static GHG results in consideration of CFs

Dynamic accounting of GHG emissions results in a large absolute difference when compared to static GWPs calculated against a 100-year arbitrary time horizon. As shown in Figure A3.27 in Appendix 3, we have a substantial methane emission at the beginning of the life cycle, primarily due to the increase in the demand of the surface materials and transportation to the construction site. Looking into the details of the process contribution, we observed that the production of steel rebars by the German manufacturers with blast oxygen furnace technology (the short-term supplier) and their transportation to Canada emits 0.011 kg CH_4/kg steel to the new construction of the ALT [210]. However, the change in the demand for steel does not continue in the later ages for M&R. We also observe a significant GWP increase up to ten years after the starting time of the emissions related to the UHI-induced electricity consumption. The largest emission of CO_2 in ALT and BAU systems comes from the binders. In fact, production of portland cement as a binder for concrete pavement by natural gas using dry kiln technology, i.e. the short-term affected supplier, results in 0.83 kg CO_2/kg cement emission (versus 0.51 kg CO_2/kg cement by long-term affected technology, i.e. preheater and pre-calciner technology with biomass fuel). The asphalt binder induces 0.43 kg CO_2/kg bitumen. Concerning demanded binders for each pavement system, i.e. 613 t cement/km pavement versus 219 t bitumen/km pavement, a significant difference of CO_2 flow in the new construction is emerged, which is linked to the difference in binder quantity and CO_2 intensiveness of the binder production process. In addition, production of high-voltage electricity through the short-term affected supplier (gas power plant in New Brunswick) emits 0.432 kg CO_2/kWh, while the quantity of CO_2 emitted by the long-term technologies is much lower than that emitted in short-term (0.033 kg CO_2/kWh) [210]. Shifting from the short-term to the long-term supplier of electricity production after 10 years can explain the sharp reduction in the UHI contribution in the GWP results, which is presented in Figure A3.22. Since the lifetime of CH_4 is much shorter than CO_2 and N_2O [183], its corresponding RF will diminish sooner than other evaluated GHGs after emission. Hence, the major contribution of GWP after methane emissions, comes from CO_2 emissions in the years after the materials production and construction phases.

One should note that the dynamic CFs results may be more or less than the static CFs results depending on the timing and quantity of emitted GHGs. In fact, limiting the dynamic CF results of GHG emissions to a fixed time-horizon brings about the consideration of GHG emissions over a smaller period (e.g., emissions occurring at year 10, 20, or 50 are effective over a period of 90, 80, or 50 years, respectively for a fixed 100-year time horizon). The difference between static CF and dynamic CF results lays in this shorter effective time of emissions. In fact, the later the emissions occur in dynamic CFs results, the shorter the time horizon used for assessing their impact on global warming when we limit the period of assessment. As illustrated in Figure A3.27 and manifested in the static CFs results, the positive quantity of GHGs induced in the early ages of the life cycle, was larger in the cumulative dynamic 100-year results compared to static CFs. However, the cumulative GHG emissions at later ages are negative, implying environmental benefits of the substitution during the use phase. The GHG emissions of the use phase resulted in a lower GWP score than that of static CFs. This is because the use phase emissions have an effect over a shorter period of time than those in the materials production and construction phases. In other studies, Levasseur et al.[163] compared the substitution of gasoline with corn ethanol and observed a similar reduction in dynamic CF results compared to those with static CFs. This reduction was due to the extensive GHG emissions in the ethanol scenario during the production phase, which is amplified since it occurs at the first year of the analysis period. In a wastewater treatment plant, Shimako et al. reported that when the major GWP impacts come from methane and there was no difference between the dynamic and static CFs results after 100 years since the RF effect of methane is greatly reduced in 100 years [211]. On the other hand, a comparative study of alternatives for buildings considered the dynamic and static CFs for calculating the buildings GWP [212]. The results showed that using the dynamic CFs tends to decrease the impact of wood houses compared to other materials, such as concrete. This decrease is because the EOL emissions occur 100 years after construction, therefore there are no CFs for EOL emissions with a fixed time horizon of 100 years, and the GWP related to the EOL incineration is not captured.

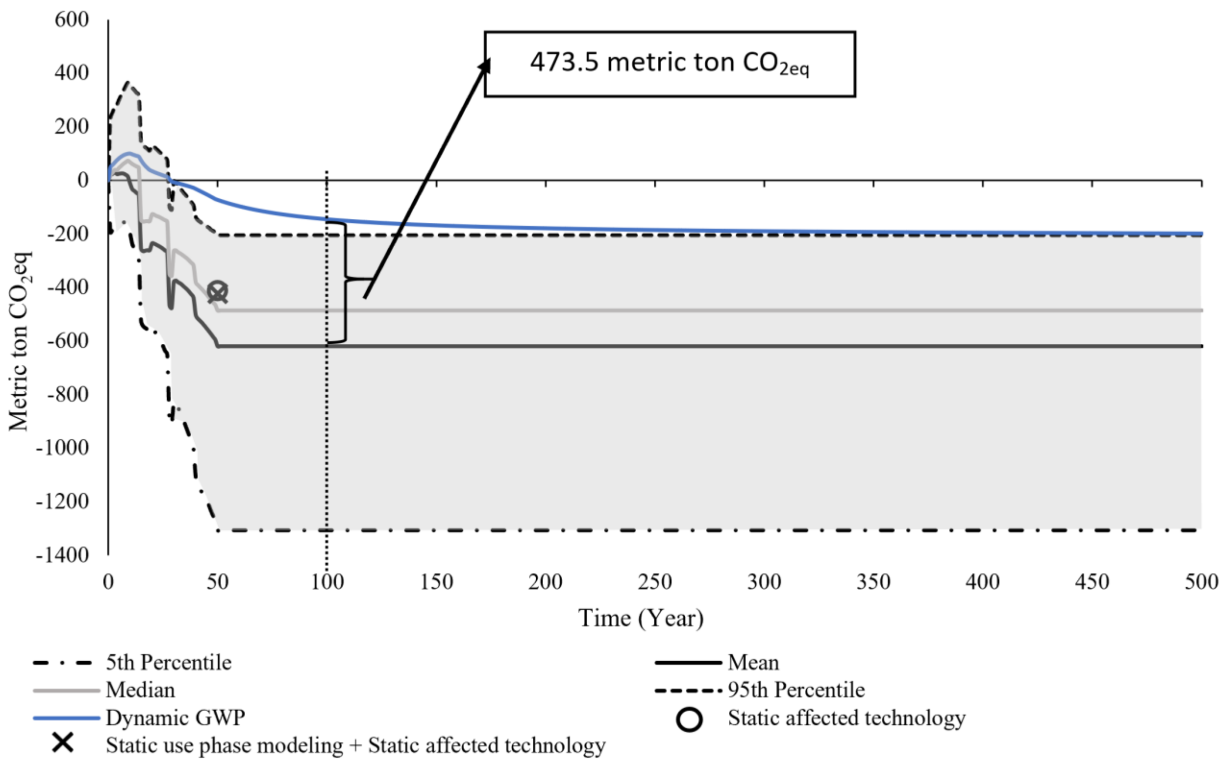

Figure 5.3. Comparison of static GWP fixed CFs for time horizons of 100 years (black continuous line) based on IPCC 2013 and dynamic CFs results (blue continuous line) for the substitution of ALT with BAU.

The total cumulative results at the end of life of the pavement were considered constant for the years after 50 for the purpose of comparison with dynamic results. In the static affected technology scenario, we used a similar modeling framework to the dynamic, except that we only linked the demand to long-term affected technologies; static CFs were included. In static use-phase modeling with static affected technology, in addition to limiting the affected supplier to long-term technology and using static CFs, we computed the use-phase impacts with static inputs. A list of input parameters is available in Appendix 4 tables, Table A3.1 in Appendix 3.

5.4.3 Individual and combined analysis of uncertainty and variability sources

Figure 5.4 illustrates a hierarchical contribution analysis of variance at two levels of uncertainty and variability sources and parameters for the four damage categories. Variability of data plays the leading role in the uncertainty of the results in the CC, HH, and EQ categories. The thickness of surface overlays and the ALT surface milling can change due to the equipment conditions and the technology used for M&R. This variation in the overlay thicknesses in the M&R and construction phases might be considered negligible (e.g., ±2 cm variation in asphalt overlay for M&R) as it can induce a variation of 234 m^3 of asphalt materials. Gregory et al. [160] examined the variation of pavement thicknesses for initial construction and found this input to be one of ten parameters that contribute most to GWP results. Adding M&R thickness variations, as we did in this study, we can consider the thickness variation impact through the life cycle and we obtain results which are more significant than those obtained by Gregory et al. In addition, the pavement service life, which is one of the key parameters in reference flows calculation, resulted in an 11-15% contribution in the variance of the damage categories. The air temperature variability contributed 8-16% to the variance of the damage results; less for CC and more for R category. Temperature affects the rigidity of pavements and determines whether the UHI effect induces cooling or heating demands, which are two of the heaviest weighted components in all the damage category results (See Figure A3.26 in Appendix 3).

The quality of the data obtained from proxy processes is also significant according to Figure 5.4, particularly for the R category. Car and truck fuel consumption dependent on IRI and rigidity of pavements plays a major role in parameter uncertainty contribution. The basic uncertainty factor with a significant value of 0.12, i.e., the intrinsic uncertainty related to the epistemic errors in sampling size [181] associated with the foreground of the transport-related unit processes is the major reason for the 23-43% contribution to the variance of the results. Dividing the contributed parameters among the related life cycle phases, we observed that more than 90% of the total variance comes from the model, variability and data quality of parameters related to the IRI component as illustrated in Figure A3.28 in Appendix 3. Therefore, we can consider this component a priority when resources are available for model refinement. These results did not include the consequential modeling uncertainty. One way to improve the uncertainty analysis of this study is to develop a method for incorporating modeling uncertainty associated with the consequential framework, where affected suppliers are determined. Looking at electricity generation in Denmark, Mathiesen et al. showed the uncertainty of the CLCA methodology by providing specific examples in different time frames [213]. Developing a framework to address consequential modeling uncertainty in the context of LCA, a means to quantify, interpret, or even communicate it, is an important outlook to provide for this section.

One should note that the uncertainty results of this stage do not incorporate the variation of parameters, assumptions, and modeling in the goal and scope definition and the impact assessment method. As mentioned by Linkov and Burmistrov, the model uncertainty of exposure point concentrations, temporal changes in exposure point concentrations, and particularly, application to future scenarios, formulation, model implementation, and parameter selection originating from subjective interpretation, can extensively affect the selection made through an impact assessment [214]. Moreover, the uncertainty related to consequential LCA modeling was no incorporated to the variation sources. One way to improve the uncertainty analysis of this study is developing a method to incorporate modeling uncertainty associated with the consequential method, where affected suppliers are determined. In fact, framing the model in different ways to identify the affected technologies may result in a wide range of calculation outputs. For example, looking at electricity generation in Denmark, Mathiesen et al. showed the uncertainty of the CLCA methodology by providing specific examples in different time frames [213]. The use of these alternative models is one of few available techniques to treat this model uncertainty [214]. The inclusion of these uncertainty sources to the previously discussed sources of uncertainty and variability might result in a limitation in the capabilities of LCA to serve as a reliable tool for this assessment.

Figure 5.4. Sources of variability and uncertainty and inputs to the variance in each category based on correlation coefficients of the normalized squared Spearman rank. LT= Long-term, ST= Short-term, IRI= International roughness index, M&R= Maintenance and repair, BAU= Business-as-usual scenario, P_{ij}= Dimension functions in rigidity model, T_a= Atmospheric transmittance factor.

The use of the dynamic consequential model implicates pavement alternatives as a means to transition to lower environmental footprints for road transportation. To achieve the energy saving potential of pavements, necessary policy measures include a revision of subsidies for energy household consumption and innovative road transportation technologies. The use-phase of pavements and, particularly, the responses of suppliers to demands can be effectively influenced by interventions in the energy sector. In regard to the pavement use phase, the interaction of the model parameters in this phase with the inherent variations in the world, i.e., the true differences in time-dependent and spatial-related parameters or user behavior and is manifested in uncertainty analysis, implies the limitation of improving the accuracy of the results.

Although not established as a policy in the province of Quebec, there is a probability of developing a mature market for electric vehicles in the long term. Depending on the cost of infrastructure development or operation, the electric vehicles might be the affected supplier in different time horizons. Particularly in regions with investments in low-cost clean technologies of electricity generation, the use phase-induced demands for vehicles fuels may revert the conclusion when an alternative scenario manifests its environmental benefits through the fuel-saving properties. The evidence for the importance of the future energy strategy is in electricity provision in Quebec, as we show for the UHI effect, where the wind electricity projection in the long term diminished the impact of heating demand increase resulted from shifting from darker to a lighter color pavement. Nonetheless, to avoid underscoring the impacts of the demand changes a more precise analysis is required, since the fluctuation and peak demand in intermediate flows, such as electricity, need to disaggregate intra-annual data [215]. This discussion can be more meaningful underneath the scenario considering urban densification in the studied region, reflecting the importance of urban planning.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Research contributions

This work exhibits several original contributions to the subject of pavement LCA. Generally, the main constraints of CLCA are to do with its temporal and spatial aspects. While the spatial limitations can be solved by aggregation of flows in regional or national levels, for example, the inclusion of the time factor into the consequential assessments remains a challenge and the main topic for a multitude of studies. The proposed dynamic framework improves the accuracy of results in such studies since timing of emission highly influences the severity of the impacts. In addition, the inclusion of the time factor has been proven essential not to obscure the representation of the real-case scenarios. Therefore, the dynamic CLCA proposed in this thesis allows an improved calculation of the potential consequences resulting from changes taking place in time-variant pavement system. Concerning the limitations related to the dynamic LCA application, the dynamic CLCA method avoids the constraints linked to the choice of the time horizon by allowing an impact assessment over both the short and the long terms. As for the narrow availability of the dynamic inventory, the new technique can surpass this limit using temporal data. As a result, the CLCA model incorporating the temporal variability along with the economic aspects is expected to be one of highly accurate and reliable methodology to be used in infrastructure sectors, specifically the ministry of transportations. The novel dynamic LCI can open the door for a more realistic time-dependent LCA of pavement selection. In addition, provision of a dynamic framework of consequential LCI can facilitate reaching the goal of incremental accuracy by enabling one to use the dynamic CFs.

The industrial field, specifically the pavement construction stakeholders can benefit from the outcomes of this dissertation. In a world constrained by environmental regulations and limited budgets, the proposed methodology can help pavement stakeholders to have a more accurate estimation of the environmental footprint of their decision. Moreover, LCA software tools will help model the environmental impacts of pavements with data support and presentation.

Considering the consequential framework and the dynamic aspect of the pavement inventories, a publicly available tool can be developed to estimate the environmental impacts of pavements. It can be expected that the model will be used for a database or software dedicated to pavement decision-making.

6.2 Conclusions (EN)

So far, several environmental impacts of pavement alternatives, such as climate change, have been studied through life cycle assessment (LCA) and within an attributional context. However, the discussed market behavior to the demand changes cannot be captured when using attributional LCA. Considering the supply and demand changes in policy-making, an analytic tool with a consequential framework is required to capture the link of processes in the product system to the extent that they are expected to change as a consequence of a change in demand for the functional unit. In addition, as the changes in physical conditions of pavements can vary as a function of time, the consequential life cycle inventory is time-dependent. The temporal distribution of impacts within the pavements' life cycle is not fully captured in previous studies. Nevertheless, the uncertainty due to the calculation of all these parameters and the inherent changes in the world, where the LCA calculation has not been applied yet, should be considered to estimate the robustness and precision of the results. In fact, to reach a comprehensive methodology of the uncertainty analysis, it is essential to consider the interdependencies. Otherwise, ignoring the relationship between different uncertainty sources and parameters may lead to an entirely different conclusion compared to those obtained through an independent sampling in each iteration. The CLCA studies are inherently comparative since there is always a business-as-usual scenario that can be replaced by an alternative scenario with the same level of functionality. Several comparative studies have also been performed based on an attributional framework. In comparative studies and particularly in pavement life cycle studies, sources of uncertainty and variability are correlated with each other. In this sense, a flexible procedure applicable to different investigation tools is required to include all the possible uncertainties and variabilities with various probability distributions in the analysis.

For these reasons, the objective of the research project is to develop a framework to integrate the dynamics of pavement life cycle impacts and at the same, to consistently treat the uncertainty and variability sources. This is done by first, defining the uncertainty analysis framework and applying the framework to an attributional case study. After developing the dynamic consequential, the uncertainty and variability were treated using the model proposed in the previous stage. The main results show that:

- By applying the proposed method to a case study, it was shown that simplifying pavement CLCA framework through neglecting dynamic changes result in notable diversions in the impacts. In fact, using a single long-term affected technology for each unit process leads to an underestimation in the environmental benefits of substituting asphalt with concrete in the climate change, human health, and resources categories. While in ecosystem quality, we found that singling out the long-term affected technology and ignoring the dynamic aspect of the time-dependent parameters can increase the environmental benefits of the substitution decision by 114% of the dynamic results. Lack of consideration for the temporal profile of the GHG emissions by using static characterization factors tends to overestimate the GWP benefits of substituting asphalt with concrete by 105%.

- Investigating the contribution of GHGs, we observed a substantial quantity of methane emission at early ages of the life cycle. This emission is majorly due to the increase in the demand of the surface materials and transportations to the construction site as a consequence of replacing asphalt with concrete. Then, in the following years, we observed a significant GWP increase up to ten years after the starting time of the emissions. This increase is related to the urban heat island-induced electricity consumption. Since the lifetime of CH_4 is significantly lower than CO_2 and N_2O, its corresponding RF will diminish sooner than other evaluated GHGs after the emission time. Hence, the major contribution of GWP after methane emission comes from CO_2 emissions in the years after the materials production and construction phases.

- We also observed an increase in the environmental damages at the beginning of the life cycle, when the material production and construction phases occur, in all the damage categories, except for resources. The impacts on ecosystem quality, human health, and climate change due to producing concrete are more than those in asphalt, while the feedstock energy embodied in crude oil (equivalent to 51.2 MJ/kg) leads to a higher damage in resource consumption than the concrete scenario in the initial construction phase.

- Sharp decreases in the score of all the damage categories at the ages of 15 and 28 years are related to the avoided demand for maintenance and repair materials and machinery of asphalt scenario when a new overlay system will replace the aged one. For the ecosystem quality, the sharp decreases in the damage score are more significant than those in other categories since 208 mg Aluminum and 16.7 mg Zinc per kg landfilled biomass, emitted by the wood ash to the soil, resulted in 2.073 PDF.m^2.yr per kg bioasphalt (i.e. the long-term affected technology for bitumen production). Compared to other studies, these toxicity emissions were not previously observed majorly due to the use of other LCIA method that cannot capture the impacts of aluminum emitted to the soil.

- The incorporation of heating and cooling demand changes due to the effect of urban heat island in long and severe winters and mild summers, such as those prevailing in Quebec, results in a net increase in the electricity demand (46±9 MWh/yr/km pavement) as a consequence of switching from asphalt to concrete. At least 75% of the induced impacts in the four damage categories took place during the short-term period and was caused by the increase in the electricity production in a gas power plant in the U.S. (i.e. the short-term affected supplier for electricity).

- In the next stage, it was shown that assessing the individual and combined effects of common uncertainty and variability sources is feasible both in attributional and consequential frameworks. The proposed framework was applicable to commercial LCA software and spreadsheet-based application including the Monte Carlo simulation.

- In the attributional framework, the analysis results show that the uncertainty due to allocation choices is effective on the preferred scenario in ecosystem quality.

Furthermore, a significant variation in the global warming and human health results was obtained due to the possible variation in construction materials and methods. On the contrary, the uncertainty due to the data quality shows relatively high uncertainty in the selection of the preferred scenario in the ecosystem quality category. Therefore, disregarding one of these uncertainty and variability sources will jeopardize reaching a certain and robust conclusion in the endpoint categories.

- In the consequential framework, the inherent variability of the pavement life cycle plays the leading role in the uncertainty of the results in climate change, human health, and ecosystem quality categories. The thickness of surface overlays and the concrete surface milling can change due to the equipment condition and the technology utilized for repair. This variation in the overlay thicknesses in repair and construction phases might be considered negligible (e.g. ±2 cm variation in asphalt overlay for repairing) however, it can induce a variation of 234 m^3 of asphalt materials variation.

- The pavement service life, which is one of the key parameters in the reference flows calculation, resulted in 11-15% contribution in the variance of the damage categories. The air temperature variability contributed 8-16% to the variance of the damage results, less for climate change and more for the resources category. In fact, the temperature affects the rigidity of pavements and determines whether the urban heat island effect induces cooling and heating demands.

6.3 Conclusions (FR)

Jusqu'à présent, plusieurs impacts environnementaux des alternatives de chaussées, tels que le changement climatique, ont été étudiés à travers l'analyse du cycle de vie (ACV) et dans un contexte attributionnel. Cependant, le comportement du marché discuté aux changements de la demande ne peut pas être capturé lors de l'utilisation de l'ACV attributionnelle. Considérant les changements dans l'offre et la demande, un outil analytique avec un cadre conséquentiel est nécessaire pour capturer le lien des processus dans le système de produits dans la mesure où on s'attend à ce qu'ils changent à la suite d'un changement de la demande. De plus, comme les changements dans les conditions physiques des chaussées peuvent varier en fonction du temps, l'inventaire du cycle de vie qui en résulte dépend du temps. La distribution temporelle des impacts dans le cycle de vie des chaussées n'est pas entièrement prise en compte dans les études précédentes. Néanmoins, l'incertitude due au calcul de tous ces paramètres et les changements inhérents au monde, où le calcul de l'ACV n'a pas encore été appliqué, devraient être pris en compte pour estimer la robustesse et la précision des résultats. En fait, pour parvenir à une méthodologie complète de l'analyse de l'incertitude, il est essentiel de considérer les interdépendances des paramètres. Autrement, ignorer la relation entre les différentes sources d'incertitude et les paramètres peut mener à une conclusion entièrement différente de celle obtenue par un échantillonnage indépendant à chaque itération. Les études ACVC sont intrinsèquement comparables car il existe toujours un scénario de statu quo qui peut être remplacé par un scénario alternatif avec le même niveau de fonctionnalité. Plusieurs études comparatives ont également été réalisées sur la base d'un cadre attributionnel. Dans les études comparatives et en particulier dans les études sur le cycle de vie des chaussées, les sources de dispersion sont corrélées les unes avec les autres. En ce sens, une procédure souple applicable aux différents outils d'investigation est nécessaire pour inclure toutes les incertitudes et variabilités possibles avec différentes distributions de probabilité dans l'analyse.

Pour ces raisons, l'objectif du projet de recherche est de développer un cadre pour intégrer la dynamique des impacts du cycle de vie de la chaussée et, en même temps, de traiter de manière cohérente les sources d'incertitude et de variabilité. Cela se fait d'abord en définissant le cadre d'analyse de l'incertitude et en appliquant le cadre attributionnel. Après avoir développé l'effet corrélatif dynamique, l'incertitude et la variabilité ont été traitées à l'aide du modèle proposé à l'étape précédente. Les principaux résultats montrent que:

- En appliquant la méthode proposée à une étude de cas, il a été démontré que la simplification du cadre ACVC des chaussées en négligeant les changements dynamiques entraînait des détournements notables des impacts. En fait, l'utilisation d'une seule technologie affectée à long terme pour chaque processus d'unité conduit à une sous-estimation des avantages environnementaux de la substitution de l'asphalte par du béton dans les catégories changement climatique, santé humaine et ressources. Tandis que dans la qualité de l'écosystème, nous avons trouvé que cibler la technologie affectée à long terme et ignorer l'aspect dynamique des paramètres dépendant du temps peut augmenter les avantages environnementaux de la décision de substitution de 114% des résultats dynamiques. Le manque de considération pour le profil temporel des GES en utilisant des facteurs de caractérisation statique a tendance à surestimer de 105% les avantages du changement climatique de l'asphalte de substitution avec le béton. Néanmoins, les valeurs dynamiques du CC se situent entre les 5e et 95e centiles de ceux qui ont des facteurs de caractérisation statiques.

- En examinant la contribution des GES, nous avons observé une quantité importante d'émissions de méthane aux premiers âges du cycle de vie, principalement en raison de l'augmentation de la demande de matériaux de surface et des transports vers le site de construction. Puis, au cours des années suivantes, nous avons observé une augmentation significative du CC jusqu'à dix ans après le début des émissions. Cette augmentation est liée à la consommation d'électricité induite par les îlots de chaleur urbains. Étant donné que la durée de vie du CH_4 est très inférieure à celle du CO_2 et du N_2O, sa FC correspondante diminuera plus rapidement que les autres GES évalués après le temps d'émission. Par conséquent, la contribution majeure du CC après les émissions de méthane provient des émissions de CO_2 dans les années qui suivent la production des matériaux et les phases de construction.

- Nous avons également observé une augmentation des dommages environnementaux au début du cycle de vie, lorsque les phases de production et de construction de matériaux se produisent, dans toutes les catégories de dommages, à l'exception des ressources. La qualité de l'écosystème, la santé humaine et le changement climatique du béton sont supérieurs à ceux de l'asphalte, tandis que l'énergie du pétrole brut (équivalent à 51,2 MJ / kg) entraîne des dommages plus importants dans la consommation de ressources que le scénario du béton.

- Les fortes diminutions du score de toutes les catégories de dommages à 15 et 28 ans sont liés à la demande évitée de matériaux d'entretien et de réparation et à la machinerie du scénario d'asphalte lorsqu'un nouveau système de recouvrement remplacera le vieux. Pour la qualité de l'écosystème, les fortes diminutions du score de dégâts sont plus importantes que celles des autres catégories, puisque 208 mg d'aluminium et 16,7 mg de zinc, émis par les cendres de bois, aboutissent à 2,073 PDF.m^2.yr par kg de bio asphalte (c'est-à-dire la technologie affectée à long terme pour la production de bitume). En comparaison avec d'autres études, ces émissions de toxicité n'ont pas été observées auparavant principalement en raison de l'utilisation d'une autre ACVI qui ne peut pas capturer les impacts de l'aluminium sur le sol.

- L'incorporation des changements de demande de chauffage et de refroidissement attribuable à l'îlot de chaleur urbain dans les hivers longs et rigoureux et les étés doux, comme au Québec, entraîne une augmentation nette de la demande d'électricité (46 ± 9 MWh / an / km chaussée). Au moins 75% des impacts induites dans les quatre catégories de dommages ont eu lieu à court terme et ont été causées par l'augmentation de la production d'électricité dans une centrale à gaz aux États-Unis (fournisseur à court terme affecté à l'électricité).

- À l'étape suivante, il a été démontré que l'évaluation des effets individuels et combinés des sources communes d'incertitude et de variabilité est possible à la fois dans les cadres attributionnel et conséquentiel. Le cadre proposé était applicable aux logiciels d'ACV commerciaux et aux applications reposant sur des tableurs, y compris la simulation de Monte Carlo.

- Dans le cadre attributionnel, les résultats d'analyse montrent que l'incertitude due aux choix d'allocation, et plus précisément, l'incertitude due au choix d'allocation, est efficace sur le scénario privilégié de qualité de l'écosystème. De plus, une variation significative des résultats du réchauffement climatique et de la santé humaine a été obtenue en raison de la variation possible des matériaux et des méthodes de construction. Au contraire, l'incertitude due à la qualité des données montre une incertitude relative dans la sélection du scénario préféré dans la qualité de l'écosystème. Par conséquent, le fait de ne pas tenir compte de l'une de ces sources d'incertitude et de variabilité mettra en péril l'atteinte d'une conclusion certaine et solide dans les catégories de paramètres.

- Dans le cadre conséquentiel, la variabilité des données joue un rôle prépondérant dans l'incertitude des résultats concernant les changements climatiques, la santé humaine et les catégories de qualité des écosystèmes. L'épaisseur des revêtements de surface et le fraisage de surface du béton peuvent changer en raison de l'état de l'équipement et de la technologie utilisée pour la réparation. Cette variation des épaisseurs des chaussées dans les phases de réparation et de construction peut être considérée comme négligeable (par exemple, une variation de ± 2 cm du recouvrement d'asphalte pour la réparation) alors qu'elle peut induire une variation de 234 m^3 de variation des matériaux d'asphalte.

- La durée de vie des chaussées, qui est l'un des paramètres clés dans le calcul des débits de référence, a permis une contribution de 11-15% dans la variance des catégories de dommages. La variabilité de la température de l'air a contribué de 8 à 16% à la variance des dommages, moins pour le changement climatique et plus pour la catégorie de ressources. En fait, la température affecte la rigidité des chaussées et détermine si l'effet d'îlot de chaleur urbain induit des demandes de refroidissement et de chauffage.

6.4 Recommendations

Based on the obtained results, the following recommendations are proposed for future studies in the field of pavement LCA:

- There is a probability of developing a mature market for electric vehicles in the long-term, but it has not been established as a policy in certain geographical contexts, e.g. Quebec. Depending on the cost of infrastructure development or operation, electric vehicles might be the affected supplier in different time horizons. Particularly in regions with investments in low-cost clean technologies of electricity generation, the use phase-induced demands for vehicles fuels can revert the conclusion when an alternative scenario manifests its environmental benefits through the fuel-saving properties.

- The importance of the future energy strategy is in electricity provision in Quebec as we show for the UHI effect. In fact, the wind electricity projection in long-term diminished the impact of heating demand increase resulted from shifting from darker to a lighter color pavement. However, to avoid underscoring the impacts of the demand changes, a more precise analysis is required since the fluctuation and peak demand in intermediate flows, such as electricity, needs to be utilized at higher temporal resolution. This discussion can be more meaningful underneath the scenario considering urban densification in the studied region, reflecting the importance of urban planning.

- The monthly air temperature plays a significant role in UHI-induced electricity consumption. Therefore, we examined the effect of temperature variability in the geographical context of the case study and included this effect in the statistical results. In addition, as a level of simplification, we considered heterogeneous urban neighborhoods to be uniformly distributed buildings of equal story and size with a constant household number. The cloud transmittance factor can also play an important role towards improving the precision of calculating the albedo effect. In future work, to approach the reality of an urban neighborhood and the actual transmittance condition of shortwave radiations, actual geometry conditions and meteorological variables should be used to increase the accuracy of the model through geographic information systems.

- What can be done more in terms of the uncertainty and variability treatment is that variability sources in background processes (e.g. source of raw materials and bitumen) can bring a new outlook for the results. In addition, when applying a methodological choice to a system, the choice should be consistently applied in the background processes. For example, the allocation rule must not be limited to merely to the foreground multifunctional processes. Using an open source library, such as Ocelot, may open the doors for defining a consistent rule in a complex database, such as ecoinvent. This consistency should be applied to a consequential database as well, when affected technologies for foreground unit processes are identified and must be deployed for the whole complex system of the database. Further research is required to investigate these details of modeling.

- Another path towards improving the uncertainty analysis in pavement LCA studies is to develop a method for incorporating modeling uncertainty associated with the consequential framework, where affected suppliers are determined. Looking at electricity generation in Denmark, Mathiesen et al. showed the uncertainty of the CLCA methodology by providing specific examples in different time frames [34]. Developing a framework to address consequential modeling uncertainty in the context of LCA, a means to quantify, interpret, or even communicate it, is an important outlook to provide for this section.

- Normalizing the midpoint and endpoint results helps decision-makers to examine the importance and magnitude of the results, to communicate on these results, and as a decision support tool. Another area that merits further investigation is the normalization and the effect of category weighting on the final decision. If to be done, it is critical to asses the uncertainty associated with the calculation of the normalization factors assigned to each impact category.

Focusing on the critical review of this dissertation, the following research gaps can be an area of improvement for pavement LCA studies:

- In pavement LCA, noise is generated in different phases, such as construction, use, and EOL. The integration of noise impact category and providing a link to human health damage for roads and construction equipment can be a topic of future research. The noise impact has not been captured in any LCA database. In addition, the impact of noise annoyance will likely become smaller as less noise generating technologies are expected to be adopted. Therefore, it will be helpful to investigate the potential trade-off between the avoided direct impact due to noise reduction and the life cycle environmental impacts of the pavement technologies that reduces pavement-tire noise.

- One of the parameters that can be influenced by the schedule and the types of maintenance and repair is traffic delay. The interruption of traffic by lane closures in construction work zones should be considered when road maintenance and repair activities are performed. A comprehensive and geographically specific data is required to consider traffic circulations and detours when the repair activities, such as resurfacing, are undertaken. The importance of different parameters such as, vehicle types and speed reduction, real-time traffic volume, and traffic congestion hours can bring a new insight into the dynamic model.

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Appendix 1.

Review article - Life cycle assessment of pavements: Reviewing research challenges and opportunities

Avant-propos

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Abstract

An extensive growth in pavement life cycle assessment (LCA) studies is noticed in recent years. Current literature in pavement LCA demonstrates a wide range of implications on environmental burdens associated with the pavements. However, immature parts still remain, needing further research, in the next years, in different stages of pavement LCA. Most of these papers focused on the implementation of new technologies on pavements construction, the use of recycled materials, and the investigation of various phases of the pavement life cycle rather than improving the applicability and the adequacy of LCA methodology to the pavement problems. These stages are based on ISO 14040 and 14044 frameworks: the goal and scope definition, the inventory analysis, the life cycle impact assessment and interpretation. In this paper, a comprehensive review (i.e. a critical review and research gaps investigation) of LCA studies on pavements was conducted. The presentation comprises (not an extensive list) inventory analysis such as surface roughness, noise, lighting, albedo, carbonation, and earthwork in addition to locally applicable data collection, consequential and temporal consideration of pavement life cycle, and sensitivity analysis. Addressing these inadequacies will permit enhanced pavement LCAs studies. This will then be useful for policy makers, project managers, construction engineers, and other stakeholders in identifying prospective in sustainable development of the pavement sector.

Keywords: Pavements, life cycle assessment (LCA), Asphalt, Concrete

Highlights:

- An extensive review of pavement LCA publications between 2010 and 2015 is carried out.
- Research gaps are identified and organized following ISO 14040 and 14044 framework.
- Methodological choices and data set selections on pavement LCA are discussed.
- Suggestions on dealing with such problems in future research are provided when possible.

1. Introduction

Numerous roads are being constructed worldwide. It was evaluated that the major portion of the road investment is related to materials and their transportation costs [1]. There is not only considerable investment for building these roads, but also for their maintenances during their life span. As a matter of fact, for 2030, Federal Highway Administration of the U.S. Department of Transportation reported that 65 to 83 billion $ were the estimated annual budget for repair and maintenance of existing highways and bridges in the U.S., which is about 40% of spent budget on all related expenses in 2010 [2]. The same trend was observed in the province of Quebec (Canada), as the major investment of government, referring to 2014-2024 infrastructures plan investments, belongs to road networks with 22.8% of total budget. The investment for the upcoming 10 years is even more than that for health and social services. The most noteworthy in the plan is that 70% of the earmarked investment were assigned to maintain roadways and structures in good condition [3]. In European countries such as Denmark, more than 40% of public sector budget was assigned to road network [4]. In Brazil, 12.5% of total 4 years budget in São Paulo was spent on roadways development and maintenance [5]. This significant contribution in region's total budget needs to be redirected to an environmental friendly road infrastructure.

In addition to the economic perspective, road projects are also known for their considerable energy and environmental (i.e. emissions) impacts. For example, it was reported that more than 120 million gallons of gasoline and 35 million gallons of other types of fuels are being consumed in the U.S. highways by different types of vehicles in the roads every year [6]. Such considerable amount of fuel consumptions leads consequently to different air, water, and soil pollutions [7]. Nowadays, pavements projects' stakeholders are interested in evaluating environmental burdens by considering different life cycle stages of roads. A study has demonstrated that moving toward sustainable development in pavement construction projects can lead to lowering their Greenhouse Gases (GHG) emissions, and their life cycle cost [8]. Hence, Life Cycle Assessment (LCA) is the appropriate holistic tool that can help the project stakeholders to deal with environmental aspects of their pavements to reach the objective of sustainable pavement construction. Indeed, LCA helps to quantify, analyze, and compare environmental impacts of different types of pavement from the material extraction to their end of life. Based on ISO 14040 and 44 standards [9, 10], LCA methodology is divided into the following steps: 1) goal and scope definitions; 2) Inventory collection and analysis; 3) environmental impact assessment, and 4) interpretation of the obtained results.

Many research activities on environmental LCA of pavements have been conducted. From the late 1990's, published studies focused on different phases of pavement's life cycle, including asphalt and concrete pavements. The significant variation between the studies is mainly based on available data and different goal and scope definition definitions. The critical literature review conducted by Santero et al. provided an exhaustive summary of application of LCA on pavement until 2011. They presented recommendations and necessary actions that should be taken to fill the identified research gaps with respect to construction, use and End of Life (EOF) phases of pavement's life cycle [11, 12]. As can be observed in Figure A1.1, since 2011, number of publications in recent years increased. This reflects the increased attention of using LCA in assessing the environmental burdens of pavements. Most of these papers focused on the implementation of new technologies on pavements construction, the use of recycled materials, and the investigation of various phases of the pavement life cycle rather than improving the applicability and the adequacy of LCA methodology to the pavement problems [13-16].

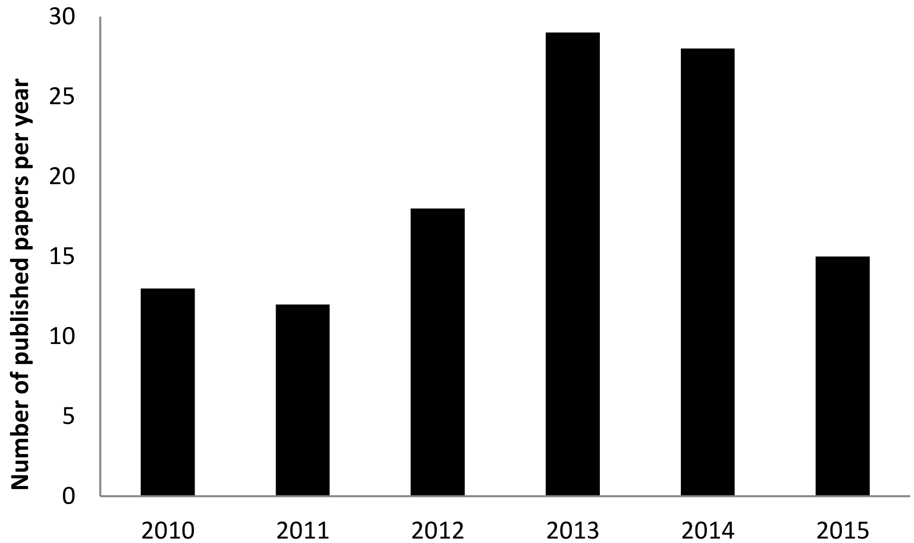

Figure A1.1. Number of articles on pavement LCA since 2010. (Search on Scopus Web site on key word "life cycle assessment" AND "pavement", available by August, 2015 [17]).

The objective of this review is to highlight issues on modeling life cycle environmental impacts of pavement. Methodological choices and data set selections are also discussed. Finally, key challenges and research opportunities on LCA pavements are summarized and suggestions on how to deal with such problems are provided when possible.

The emphasis will be given to recent papers published since the latest literature review conducted by Santero et al. in 2011. The paper is organized following the ISO 14040 and 14044 frameworks (as shown in Figure A1.2). Section 2 highlights the main findings in goal and scope definition step and its comparison along the reviewed papers. Section 3 includes inventory analysis, while section 4 includes impact assessment and interpretation main findings and suggestions.

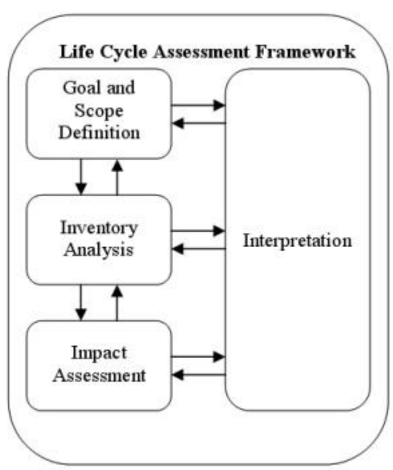

Figure A1.2. Life cycle assessment (LCA) framework according to ISO 14040 and 14044 [9].

2. Goal and Scope Definition

During the goal and scope definitions, the aim of LCA, its intended audience and also its application must be highlighted. In addition, the scope of the study must be defined. The latter includes defining the function of the pavement, functional unit (FU), reference flows, and the system boundary. When two or more product systems are compared, FU and system boundary definition play a key role in the LCA results [18].

Table A1.1 shows the G&S definitions elements presented in the reviewed papers. It is worth noting that the major cited papers in Table A1.1 and also the reviewed ones, comparing different type of pavements, shows a significant heterogeneity of functional units and other components. LCA standards such as ISO 14040 and 14044 have no technical details on, for example, phases and processes that should be included in the assessment, life spans that should be analyzed, or what are the minimum data that should be considered in the LCA modeling. Beyond the inconsistencies between publications, the significant differences in calculated life cycle environmental impact results make their comparison simply impossible. GOAL AND SCOPE definitions variations, and consequently on LCA results are explained in more details in the sub-sections.

Table A1.1. Goal and scope variations as function of the assessed region

Region	Study reference	Functional unit (FU)	Lane width (m)	Shoulder width (m)[a]	Thickness (cm)[b]	Roadway type	Type and number of pavement: Conventional concrete	Asphalt	Other	Analyzed period (years)
North America										
Colorado	[19]	1 Km lane of a four lane road	-	3.66, 3.05	33, 20.3	Interstate highway	2	1	-	40
Illinois	[20]	1 Mile lane of a road	-	1.8	30.5	-	-	4	-	45
Missouri	[21]	Not mentioned	3.6	3.6	28, 34.3	Interstate highway	1	1	-	50
Michigan	[22, 23]	10 Km of a 4 lane road	3.6	1.2, 2.7	17.5, 19, 10	Interstate highway	1	1	1[c]	40
California	[24]	4 different FUs[d]	-	-	-	Interstate highway	2	2	-	5 (asphalt); 10 (concrete)
Virginia	[25]	5.89 Km long of a two lane road	3.6	0.6-0.9, 2.4-3	30	Interstate highway	-	2	-	50
USA	[26]	1 Km of a two lane road	3.6	1.2, 2.7	17.8-30.5, 10.2-27.9	-	8	6	-	40
British Columbia	[27]	Access to 400 acres residential area that will provide 2,310 residential units	3.4	1.5	10	-	-	2	-	50
Europe										
Italy	[28]	1 Km of a two-lane road	3.5	1.25	20	Rural carriageway	-	9	-	30
Portugal	[29]	1 Km of 6 two lanes road	3.75	1.5, 3	10-32	Interurban motorway	-	6	-	40
Spain	[30]	1 Km of a two lanes road	-[e]	-	8	-	-	4	-	40
Rest of the world	[31]	1 Km of a two-lane road	3.5	1	20-22	-	-	4	-	20
Total							**14**	**42**	**1**	**-**

[a] In case of two digits, the first one belongs to inner shoulder.

[b] In case of more than one digit, the order of thickness is similar to the type of pavement.

[c] refers to engineered cementitious composite.

[d] Two of the FUs include 10 miles length of two lanes road with 34000 and 86000 annual average daily traffic with 35 and 25% truck traffic, respectively. The other FUs consist of 5 miles length of two and four lanes roads and supporting 3200 and 11000 annual average daily traffic, which include 15 and 29% truck traffic, respectively.

[e] Total road width including lanes and shoulders were implicitly mentioned 13 meters.

2.1 Functional Unit

ISO 14040 defines FU as "quantified performance of a product system for use as a reference unit" [9a]. As mentioned earlier, when two or more product systems are compared by using LCA, functional unit plays a key role in the LCA results [18]. Dale and Kim [32] reported that selecting different FUs may result in different outputs and conclusions for the same study. In pavement LCAs, FU should consider the definition of physical properties of the pavement system, including design, structural components, and material properties. FU must also reflect effective exterior factors on the pavement, such as traffic load. In a comparative study of pavement LCA, FU acts as a reference unit to which all inputs (material resources and energy) and outputs (emissions to air, water, and soil) are normalized.

Santero et al. [12a] mentioned that variation of FUs in pavement LCA studies makes it impossible to compare the results, and to assess their variations following different FU. Similarly to pavement LCA, this observation is reported in LCA's dealing with different case studies [33]. In order to make LCA conclusions more robust, it will be interesting to systematically implement different FUs, as a sensitivity analysis, as done by Loijos et al. [34], who implemented 12 different FUs to analyze 12 types of concrete pavements. The same approach was also followed by Wang et al. [24] and Santos et al. [35].

In some studies, presented in Table A1.1, the information corresponding to the road specifications were not stated in FU definition. Readers should keep in mind that it cannot be totally appropriate to reflect road functions if the roadway classification (interstate, urban, rural, and pedestrian) and its lane width in addition to the number of lanes are not taken into account. By adding characteristics, the approximate average daily traffic within the FU is implicitly reflected. Also, this makes it easier for LCA practitioners to take the advantage of available case studies and apply them for their own cases.

2.2. System boundaries

Referring to ISO 14040, system boundary definition involves the selection of activities and processes included within the life cycle phases of the pavement [9a]. It also involves taking into account the appropriate geographical and temporal scope such as the location and the period of the assessment. Different types of decisions are outlined based on at what level of complexity (network or specific project) and at what stage within the planning process (early planning or late planning/design) the decision is to be made [36]. Such decisions influence system boundaries selection by using attributional or consequential LCA. Selecting an inappropriate system boundary that does not reflect the assessed pavement reality may lower the degree of LCA practitioner's confidence in decision making [33].

As shown in Table A1.1, there is a significant variation in selected pavement's life spans, which ranges from 5 to 50 years. In some publications, they have chosen recommended life span by local transportation administration or based on rehabilitation program and life design of the road [21, 37]. This comes in contrast to other studies where the reason of choosing the selected life span is simply not mentioned [7, 19, 38].

Assessing the pavement system over a time horizon puts forward a major challenge. Some approaches were proposed for determining the analysis period. For example, using 1.2 to 1.5

times the longest functional design life among all alternatives is a commonly used approach when conducting a life cycle cost [39]. Consequently, the defined life span will be long enough in order to include influential factors in the use phase, like traffic growth rate. Such consideration is rarely checked in the reviewed papers. A sensitivity analysis by Reza et al. showed that expanding life span up to 70 years could substantially increase direct and indirect energy consumption by 40% in operation and maintenance phase of the pavement LCA [37].

In addition to the pavement's life span, the system boundary should also encompass the following phases: material production, pavement construction, use, maintenance and repair (M&R), and EOF. Most of the reviewed papers focused on raw materials extraction, their transportation (including equipment), construction, and maintenance and repair (M&R). However, in some studies, transportation needed during each phase (e.g. transportation after raw materials production) of the life cycle was assigned to that phase [40-42]. In contrast, other studies have considered all the transportations during life cycle as a stand-alone phase in the life cycle [7, 19, 35, 43, 44]. The M&R is also a good example of non-uniformity in pavements LCA. In some cases, M&R and construction is presented as a separate phase [7], where in others, M&R is defined as a stand-alone phase [20, 45]. EOF and use phase were frequently not considered, because of the cut-off approach[j] (in the case of EOF) [28, 38].

Since 2011, studies are increasing their focus on the use phase, by considering, for example, fuel consumption and emissions as a consequence to surface roughness and traffic delay (See Table A1.2). However, they are not the only parameters to consider during the use phase. As an example, Albedo, lighting, noise, and leachate can substantially affect the environmental impact of the pavements, and until now they still surprisingly rare in the literature. All parameters, including their contributions, are reviewed and discussed in more details in section 3.1.

2.3. Alternative scenario consideration

In comparative LCA, it is necessary to define alternative scenarios during the GOAL AND SCOPE definition. Pesonen et al. [47] defined term of scenario as an explanation of a possible future based on assumptions about the future which is to do with specific LCA applications. For example, the use of alkali activated materials (AAMs) in pavement has been investigated by some authors [48]. There are also some experiences of using AAM in pavement construction [49, 50]. However, the environmental impacts of AAM as an alternate of Portland cement concrete in the pavement life cycle have not been studied yet. Considering such prospective scenario is very challenging because of data collection regarding recent technologies.

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[j]"*The cut-off system model in short, is based on the Recycled Content, or Cut-off, approach. The underlying philosophy of this approach is that primary (first) production of materials is always allocated to the primary user of a material. If a material is recycled, the primary producer does not receive any credit for the provision of any recyclable materials. As a consequence, recyclable materials are available burden-free to recycling processes, and secondary (recycled) materials bear only the impacts of the recycling processes. For example, recycled paper only bears the impacts of waste paper collection and the recycling process of turning waste paper into recycled paper*" [46] http://www.ecoinvent.org/database/ecoinvent-version-3/system-models/allocation-cut-off-by-classification/. (20/04/2015).

Implementing recently developed construction materials (including their composition), new technological instruments in transportation industry such as new generation of tires, reduction of pollutants and energy consumption of various vehicles, and innovated strategy and policy for pavement can be considered in future scenarios for pavement LCA.

Table A1.2. Main used databases in pavement LCAs

Region	Study reference	Studied process in additional car fuel consumption	Selected database
North America			
Colorado	[31]	Traffic delay, roughness	Concrete production and End of life: Reiner,2007 [55] Bitumen: Eurobitume,2011 [56] Onsite equipment: Zapata and Gambatese,2005 [57]
Illinois	[32]	-	Pre-production: Monitoring resource consumption: US EIA[1], 2013 [54] Construction: Input –Output database, 2013 [58]
Missouri	[33]	Traffic delay , Rigidity and Roughness, Albedo, Lighting	Cement: PCA[3],2011 [59] Construction processes: International Grooving and Grinding Association, 2009 [60]; Stripple, 2001 [61] Generic data: Ecoinvent V. 2.2, 2010 [62] and USLCI[2],2012 [63]
Michigan	[34, 35]	Roughness	PCA, 2002 [64] Keoleian et al., 2005 [65] A database from SimaPro 6.0 (The used database is not mentioned)
California	[36]	Roughness	Stripple, 1998 [61] ATHENA, 2006 [66] Ecoinvent V. 2.2, 2011 [67] USLCI, 2011 [63] PCA, 2006 [68] Some other unmentioned sources
Virginia	[37]	Roughness	Aggregates: Stripple, 2001 [69] Asphalt: Eurobitume, 2011 [70] Cement: PCA, 2006 [68] All energies except electricity: GREET, 2013 [71] Electricity: US EIA, 2012 [72]
USA	[38]	Traffic delay and roughness	Materials module: PCA, 2007 [73]; Stripple, 2001 [69] Steel production: GREET V 2.7 [74]

Region	Study reference	Studied process in additional car fuel consumption	Selected database
Europe			
Italy	[39]	-	PaLATE database, 2006 [75] Transportation: Mauro, 2015 [76]
Portugal	[40]	Traffic delay and Roughness	Bitumen and Bituminous emulsion: Eurobitume, 2011 [70] Aggregates: Jullien et al., 2012 [77] Tap water: Ecoinvent V. 2.0, 2007 [78] HMA production: US EPA[4], 2004 [79] Transportation of materials, Construction equipment operation, On-road vehicles operation: EEA[5], 2013 [80] Electricity: Dones et al., 2007 [81] Crude oil: DG, 2008 [82]
Spain	[41]	Traffic delay	Raw materials and products, electricity, fuels, disposal: EcoinventV. 1, 2003 [83] Synthetic Zeolite: Fawer, 1998 [84] machinery, Fuel consumption and air emissions from the paving machines and Transportation: EEA, 2009 [85]
Rest of the world	[42]	Roughness	Consumption and emission related to Rolling resistance: Laboratory experimental Others phase consumption and emission: not mentioned

[1]U.S. Energy Information Administration, Department of Energy
[2] U.S. Life Cycle Inventory
[3] Portland Cement Association
[4]U.S. Environmental Protection Agency
[5] EMEP/EEA air pollutant emission inventory guidebook

3. Inventory analysis

Referring to ISO 14044 (see Figure A1.2), the second LCA step to conduct after the GOAL AND SCOPE definition is life cycle inventory analysis [10b]. The inventory analysis covers all collected data (and their validation) that represent life cycle phases within the defined system boundaries. Challenges with data (inventory) types, their collections and their integration in pavement LCA is discussed in the following sub-sections.

Inventory analysis of pavements is mainly subjected to difficulty during material, emissions and energy flow collection for processes modeling. LCAs are conducted by using different databases [85], such as ecoinvent[k], GaBi[l], or ELCD[m], etc. Based on Table A1.2, a significant number of databases are being used in pavement LCAs. Wang et al. [24] conducted a study comparing the environmental burden of a pavement base by using four different databases. They showed that as a result of using various databases, the environmental burden variation increases by 25%. Using localized and updated database seems, therefore, to be necessary. However, beyond these two necessary criteria, different data are still missing, and their inclusion is necessary to increase the robustness of the results. The following subsections present in more details the missing data to be included in future life cycle inventory (LCI) databases.

3.1. Pavement surface roughness

Effect of pavement surface on fuel engines consumption and emissions was recently discussed in numerous papers. Taylor and Patten showed that Portland cement concrete and composite could substantially decrease the amount of fuel engines consumption in comparison to hot mixed asphalt (HMA) [86]. In contrast, European Asphalt Pavement Association clarified that fuel consumption is less influenced by type of pavement rather than general state and road user type [35].

Akbarian et al. [87] presented a model drawing a relationship between pavement deflection and car fuel consumption. As shown in Table A1.2, surface roughness is one of the most significant parameters in pavement LCA. Studies have shown that up to 2% reduction in car fuel consumption can be achieved by 10% reduction in rolling resistance induced by surface roughness [88, 89]. Majority of research in the field of pavement LCA considered the surface roughness based on international roughness index (IRI). The IRI is the ratio of a standard vehicle's suspension motion divided by vehicle distance traveled during the measurement. The IRI will increase with the age of pavement.

Louhghalam et al. mentioned that as the car speed and temperature increased, significant difference between fuel consumption on various types of pavement was observed [90]. Based on their research, the car fuel consumption of the vehicles on asphalt pavement can be doubled at ambient temperature of 30°C compared to the consumption at 10 °C. In addition, they showed that considering car speed reduction from 80 to 20 km/h, the fuel consumption on asphalt pavement can increase from 3.5 to 8.1 L/100 km. Portland cement concrete pavement was not sensitive to the aforementioned criteria. As a result, a revision in consideration of car fuel

[k] www.ecoinvent.org

[l] http://www.gabi-software.com/international/databases/gabi-databases/

[m] http://eplca.jrc.ec.europa.eu/ELCD3/

consumption emission based on local condition and car speed seems to be necessary. The car fuel consumption in asphalt pavement LCA needs to be discussed as a temporal criterion particularly in region with significant daily, monthly and seasonal temperature.

Furthermore, tire wears and damage to freight and vehicles due to pavement deterioration need to be determined. Theoretical models and empirical investigations have reported strong effects of road surface condition on vehicle repair and maintenance needs, tire wear, and lubrication [91, 92]. As a result of pavement aging, a specific damage is included to the vehicles. Steyn et al. have shown that the amount of GHG emission which is induced in 20 mph speed of vehicle can be duplicated as an increase of IRI from 64 to 512 in/mile [93].

3.2. Noise

The noise generated by traffic is the main source of noise pollution, which threatens human health. In pavement LCA, the noise is generated in different phases that are directly related to the pavement life cycle; from raw materials extraction to the EOF. In addition to that, indirect sources should also be considered. As a matter of fact, the noise generated by tires and pavement interaction (for various types of pavement) is also a matter of concerns. This integration of noise generation opens up rooms for improvement. Several studies have been conducted on tires and road interactions. Bennert et al. [94] demonstrated that Stone Mastic Asphalt can reduce the noise generated by vehicle traffic rather than dense graded asphalt. Another study on pavement materials compared the noise generated by vehicles crossing cobblestones, dense graded asphalt, and open asphalt rubber pavements [95]. Comparing the annoyance level, they clarified that the noise, which has been recorded by tire and cobblestone pavement interaction, is the severest compared to the others. There are also some studies considering porous asphalt and dense asphalt surfaces in term of noise generation [96, 97].

However, noise data are not included in different LCA databases (such as ecoinvent [98]). In addition, the impact of noise annoyance will likely become smaller as less noise generating technologies are expected to be adopted. Therefore, it will be helpful to investigate the potential trade-off between the avoided direct impact due to noise reduction and the life cycle environmental impacts of the developed pavement reducing that noise. Such assessment is still surprisingly absent in the literature.

3.3. Lighting

Lighting energy is one of the criteria that are considered in the use phase of the pavement life cycle. Importance of lighting was investigated in some papers. Unanimously, it was demonstrated that vehicles light on asphalt pavements require 50% more lighting power than those on concrete pavement to have adequate illumination for driving [99, 100]. It was also investigated that using recycled materials such as glass in asphalt can lead to greater reflectance compared to conventional asphalt [98]. This phenomenon could be an environmental advantage of using recycled materials that must be taken into account in recycled pavement LCA. A study showed that asphalt pavement uses 720 MWh of electricity more than concrete per kilometer of the road during a 50 year life span [101]. It was also mentioned that once the contrast of surface is changing and hence, surface's retroreflection could vary significantly. The retroreflection of asphalt is increased from 24 to 32 mcd/lx/m[2n] during a certain number of years. While in concrete pavement, it is decreased from 38 to 31 mcd/lx/m^2.

Generally, the reflection of asphalt and concrete after aging will be increased and decreased, respectively. Even after awhile, they could have the same reflection [102]. As shown in Table A1.2, effect of surface roughness on car fuel consumption and emissions was measured and implemented in pavement LCA as a direct effect while, surface roughness could indirectly affect the energy consumption through the reflection of light. Taking lighting energy consumption into consideration not only helps to see the effect of surface roughness, but also can illustrate the importance of maintenance strategy of the pavement. These temporal variations in the reflection of light as a consequence to different type of pavements open up opportunities to incorporate temporal behavior in LCA.

3.4. Albedo effect

Solar reflectivity of pavements (known as albedo[o]) is an effective property of the pavement connected with climate change impact category. Higher albedo leads to a decrease in heat island effect and a decrease in direct radiative forcing (RF) [104]. A study have shown that increasing RF induced by an increase of 1% in solar reflectance, resulted to a reduction of 2.55 kg and 1.27 W/m^2 of CO_2 and RF, respectively by each square meter of pavement [105]. These estimates do not take into account the albedo as a function of time. In contrast, some researchers introduced time dependent parameters in their estimation of the amount of produced CO_2 [106, 107]. Eq. 1 shows the equation for calculation of estimated CO2 (in tone metric) based on RF [107]:

$$CO_2(t) = \frac{A \times RF \times \ln 2 \times P_{CO_2} \times M_{CO_2} \times m_{air}}{A_{earth} \times \Delta F_{2x} \times M_{air} \times AF(t)} \quad \text{Eq. 1}$$

where A is the albedo effective surface area (m^2); RF is the value of radiative forcing at the top of the atmosphere (W/m^2); P_{CO_2} is CO_2 partial pressure; M_{CO_2} is the molecular weight of CO_2; m_{air} is the total mass of atmosphere; A_{earth} is the surface area of Earth; ΔF_{2x} is the RF due to the doubling concentration of CO_2; M_{air} is the molecular weight of dry air; and AF(t)is a time dependent variable calculated using Eq. 2.

$$AF(t) = \frac{\int_0^t (0.217 + 0.259e^{-\frac{t}{172.9}} + 0.338e^{-\frac{t}{18.51}} + 0.186e^{-\frac{t}{1.186}})}{t} \quad \text{Eq. 2}$$

Where t is life span (year).

Yu and Lu [108] developed a model which is not only able to estimate a time dependent CO_2, but also made it possible to calculate in both deterministic and probabilistic way.

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[n]mcd/lx/m2define the unit millicandelas per lux per square meter

[o]Methods of calculation of albedo and more precisely the pavements type effects on solar reflectance are still in debate. Although some researchers clarified that Portland cement concrete has less urban heat island effect compared to asphalt, recent ideas decline the hypothesis based on new albedo measurement methodology [103]

M. Swanson and A. Hobbs, "Urban heat island effect: Comparing thermal and radiation effects of asphalt and concrete pavements on adjacent buildings using CFD methods," *Contact Urticaria Syndrome,* p. 33, 2014.. As a result, further research is needed to clarify the phenomenon.

Akbari et al. recently reported that albedo is highly affected by aging [109]. Implementing different scenarios and strategies on pavement maintenance would highly influence on albedo during pavement life cycle. Calculating albedo with respect to M&R strategies should be explored in future pavement LCA. In addition, new technologies affecting long-term albedo effects are going to be developed, such as photocatalytic surfacing and pavements colored with infrared reflective cool paints [110]. Environmental impacts of implementing these upcoming technologies have not been yet considered in pavement LCA.

3.5. Carbonation

One of the phenomena, which are inherently occurred in concrete life cycle, is carbon uptake or carbonation. Concrete carbonation is a process where atmospheric carbon dioxide reacts with calcium hydroxide (portlandite, $Ca(OH)_2$) of hydrated cement to form calcite. The Fick's first law of diffusion and the study by Lagerblad [111] (Eq. 3) was adopted to quantify the carbonation in concrete. Many authors used Eq. 3 to estimate CO_2 capture (kg/m^3 concrete).

$$\mathrm{CO_2} = k \times \sqrt{t} \times c \times CaO \times r \times A \times M \qquad \text{Eq. 3}$$

Where k is carbonation rate coefficient ($mm/\sqrt{year}$), which was calculated as function of concrete properties, t is service life (year), c is the quantity of Portland cement (kg/m^3 concrete), CaO is the amount of CaO in Portland cement (%), r is the proportion of calcium oxide that can be carbonated, A is the exposed surface area of concrete (m^2/kg), and M is the chemical molar fraction of CO_2/CaO. Carbonation rate coefficient for different concrete compressive strength and exposure conditions is widely varied from 0.5 $mm/\sqrt{year}$ (compressive strength higher than 35 MPa and wet exposure condition) to 15 $mm/\sqrt{year}$ (less than 15 MPa and indoor exposure condition).

Previous studies have shown the influence of multiple parameters on concrete carbonation. For example, water to binder ratio plays an important role [112]. Muntean and Böhm stated that carbonation is strongly dependent on the degree of porosity, which is a path for transporting water and CO_2 into concrete [113]. Once the concrete pavement life span is defined, CO_2 capture can be investigated during the service life. A recent study have shown that the CO_2 uptake during the service life of the structure (building) and recycling of demolished concrete is near 5.5–5.7% by the total CO_2 emission in the building life cycle carbonation and 10–12%, respectively [114]. Based on their model, other parameters such as mixture design, ambient temperature, and relative humidity have contribution in calculating depth of carbonation.
Nowadays, use of GGBFS as Portland cement replacement in concrete is widespread because of its technical, economical, and environmental advantages [115-117]. According to García-Segura et al. [118] replacing 80% of cement clinker by blast furnace slag reduced CO_2 capture by 20 % compared to ordinary Portland cement. Another study by Rossick on concrete pavement LCA have shown that 5 to 30% of the produced CO_2 during concrete production can be absorbed by the concrete pavement during use and EOF phase in 9 different scenarios [119].

However, it is important to mention that all the assessments do not encompass the trade-off with other life cycle stages and environmental impacts categories (beyond CO_2 emissions). The CO_2 concentration seems to be another crucial parameter in measuring the amount of CO_2 absorbed by concrete. According to Tam et al. [120], small CO_2 concentrations are associated with rural area where CO_2 content is about 0.03% by total gases in the atmosphere. It was stated that CO_2 concentration would be about 0.3% in metropolitan areas. Conciatori et al. [121] refer to the following CO_2 concentrations 0.015% in land, 0.036% in downtown, and 0.045% in industrial area. Regarding the significant compensation of the emitted CO_2 by concrete production, it seems necessary to include CO_2 absorption of the pavement during use and EOL phases when calculating its environmental burden. This can bring up methodological challenges for future pavements LCA.

3.6. Earthworks

One of the activities in work breakdown structure of a road construction, which includes high volume of materials, is earthwork operations. Considerable volume of land must be excavated, filled, and transported for each kilometer of the constructed road. Studies in this field are focused on optimization of cost and energy consumption in the earthworks volume and its transport [49]. It is worthy to mention rigidity of pavement is a key parameter on thickness of sub-layers and consequently the volume of earthwork. Results of a research on different scenarios of embankment and cut sections, including lime stabilization, use of recycling materials, and crushed virgin materials, have shown that there is up to 50% variation in CO_2 emission induced by the implemented scenarios [28].
Although there are many on-going research works on earthwork operation of construction phase, most of LCA studies have not taken it into consideration when comparing different alternatives. One of the reasons neglecting the earthwork refers to specific conditions of the particular project. Therefore, sensitivity analysis considering different scenarios of earthwork is worth to explore in future pavement LCA. As potential scenarios, the amount of excavated earth for road leveling could be a source of materials needed in the embankment sections, or it could supply the aggregates in non-graded concrete. Referring to the research done by Magnusson et al., reusing excavated earth can potentially save up to 14 kg CO_2 per ton of the earth [122].

4. Life cycle impact assessment and interpretation

Lack of temporal and dynamic patterns consideration on life cycle impact assessment has often been discussed as a serious constraint of LCA [123]. There are some efforts that was carried out in temporal LCA, in relation with the pavement use phase, such as carbonation, albedo [124] and, pavement roughness [23]. There are also many studies that have been conducted on dynamic characterization factors in LCA [125, 126]. For example, temporal changes are crucial when taking eutrophication [127], human toxicity [128] or the human health impact of noise [129]. In the case of acidification, annual variations in the context of environmental pollutants are also significant [130]. However, very few papers started to integrate the dynamic and temporal aspects in pavement LCA (including for impact categories). A comprehensive research on temporal life cycle impact assessment is needed, especially for systems with a long life span (such as pavements).

4.1. Sensitivity analysis

During the interpretation step, sensitivity analysis helps in understanding the impacts of the input data, methodological and hypothesis choices on the LCA results. As an example, a study by Sayagh et al. investigated a sensitivity analysis on allocation scenarios because of its assessment using blast furnace slag, as a by-product of steel production [131]. Until now, many important parameters in pavement LCA are lacking a sensitivity analysis whereas their influences on the final environmental impacts are not known. The following paragraphs aim to summarize them.

First of all, environmental impacts of supplementary cementitious materials (SCMs) and chemical admixtures in concrete pavements could take an important place in the near future and are still not included in recent concrete LCA [132]. Sensitivity analysis considering blast furnace slag as SCM in concrete has already been conducted [131]. However, there are some other conventional SCMs, such as silica fume and fly ashes, which are produced as by-products, which are missing in recent pavement LCAs. Second, various types of chemical admixtures, such as superplasticizers, shrinkage reducing admixtures, and curing compounds are common in concrete pavement construction. Although the volume of the chemical admixtures in concrete is low (compared to other ingredients e.g. cement, aggregates, and water), the environmental burden associated with their synthesis and toxicological properties is significant [133]. The environmental burdens of the admixtures are still not integrated in common LCI databases such as ELCD, Gabi, USLCI, etc. Indeed, the superplasticizer dosage in concrete mixtures can be as far as double content to produce fresh and hardened concrete performance depending on the ingredients [134]. Comprehensive sensitivity analysis (scenario based) seems to be prerequisite for different chemical admixtures to assess their environmental contribution.

Finally, as it is described in section 3.4, albedo influences urban heat island, which consequently causes significant variations in the heating and cooling energy demand of vehicles, and decreases the runoff quality. Hence, it could be of interest to integrate pavement temperature and reflectance in a sensitivity analysis. CO_2 uptake also plays an important role due to the carbonation processes. Porosity of the concrete pavement can speed up carbonation. The carbonation rate in rainy weather is low, as the rain relatively blocks concrete pores. Thereby, based on mentioned parameters, carbonation rate will be changed as the humidity and ambient temperature varies [118, 135]. A sensitivity analysis taking into account different carbonation rates is worth exploring.

4.2. Uncertainty analysis

During the interpretation step, pavement LCAs should assess the added uncertainty to the final results, keeping in mind all the of uncertainty sources: the inventory (quantity and quality) and the characterization factors of the impact methods. For example, implementing Eurobitume LCI database to an asphalt pavement LCA in the U.S leads to an uncertainty due to the fact that the information was provided based on the local conditions of European nations. Wang et al. [24] revealed that calculated energy consumption in HMA life cycle is changing as a function of selected LCI database, particularly in use phase. It was shown that the variation between the energy consumption in the use phase could be more than 80%. Despite its importance, uncertainty analyses by using Monte-Carlo simulation (for example) are still missing from the literature. Improvements in that direction are needed.

5. Conclusion and outlook

Due to diverse materials options, different construction methods, distinct maintenance/repair strategy, and their broad lifespan, the diversity of pavement projects gets easily significant. LCA research on different types of pavements increased significantly. Since 2011, the use phase has been discussed more extensively: ex. Traffic delay consequences and surface roughness on excessive car fuel consumption. Although the applied models are still diverse, recent studies are getting more and more integrated in the GOAL AND SCOPE definition rather than before. But still, some inconsistencies are present in the reviewed papers, more specifically in the definition of the functional unit and also in the selection of different life cycle stages. Such inconsistencies make pavement LCA results difficult to compare and most importantly limit their usefulness in a decision-making process.

Important challenges and research opportunities (from short and medium-term perspective) were also highlighted along the paper. Referring to ISO 14040 and 14044, these challenges correspond specifically the inventory collection stage and also to the environmental impact assessment and interpretation stage (stage 2, 3 and 4, referring to Figure A1.2). Inventory analysis-related research opportunities, summarized within Table A1.3, mainly encompass the following parameters which need to be quantified and integrated in pavement LCA: pavement surface roughness; noise; lighting needs; albedo effect; carbonation and earthworks. In addition to their integration, adapting the LCA modeling will be also a need. As an example, integrating lighting needs as a consequence to different type of pavement open rooms the consequential LCA development. Consequential LCA is the appropriate methodology to integrate changes in flows which are not directly (physically) connected the compared systems (pavements in our case). Another example could refer to the integration to the carbonation processes along the life span of concrete pavement. As a result, dynamic LCA has to be developed by disaggregating different flows, including the captured CO_2 as a function of time. Sensitivity and uncertainty analysis were also highly recommended in future pavement LCA because of the diversity materials options, construction methods, and so on, as they can only be captured by such type of analysis. Finally, the highlighted achievements for future LCA research will make possible for policy makers, project managers, construction engineers and users have a prospective perspective in sustainable development of the pavement sector.

Table A1.3. Summary of the challenges and research opportunities in life cycle inventory of pavement

Parameter	Challenges	Research opportunities
Pavement surface roughness (section 3.1)	-Consequences of surface roughness on indirect emissions induced by vehicles have not been studied	-Effect of surface roughness on vehicle repair and maintenance and tire wear must be included as a consequence of surface roughness
Noise (section 3.2)	-Generated noise in pavement LCA from cradle to grave has not been measured and integrated to quantify the human health impacts.	-Noise as a consequential use of different types of pavement needs to be investigated. -Noise integration within LCA databases need to be developed.
Lighting (section 3.3)	-Lighting as a consequence of pavement use has not been included in recent studies.	-Incorporation and calculation of lighting energy in study of pavements with various types of materials by developing a consequential LCA[p] is missing. -Temporal variation lighting energy consumption over time during the life span of the pavement needs to be developed and integrated
Albedo effect (section 3.4)	-Implementation effects of new technologies of pavement surface on albedo are missing -A consensus decision regarding to albedo effect of concrete has not been made yet.	-Further research on albedo effect of concrete and its integration within LCA needs to done.
Carbonation (section 3.5)	-Carbonation of concrete pavements has not been considered in pavement LCA.	-A constitutive model on carbonation of concern as a function of CO_2 concentration, ambient temperature, relative humidity, concrete constituents and debris grading of demolished concrete at the EOL is recommended.
Earthworks (section 3.6)	-Various volume of under layers earthworks as a result of different rigidity of pavement has not been evaluated in comparative studies.	-Significant amount of emission induced by earthworks needs to be assessed and integrated in LCA.

[p]By consequential LCA, we mean study the environmental consequences of possible (future) changes between alternative product systems [4] C. Calwell, "California State Fuel-Efficient Tire Report, Volume II, California Energy Commission," ed: January, 2003.

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Appendix 2.

Supporting information for Assessing the individual and combined effects of uncertainty and variability sources in comparative LCA of pavements

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1. Data collection and system boundary

To fulfill this functional unit, the pavements specifications are designed based on Quebec environmental conditions. The widths of the inner paved shoulder, main lanes, and outside paved shoulder are designed to be 1.3, 3.7 and 3 m, respectively. Considering slope of the pavement layers, the average thickness of surface, base, and sub-base thickness in the concrete and the asphalt pavements are presented in Table A2.1. It should be noted that the lifetime of concrete and asphalt pavement are assumed 50 and 49 years, respectively. Hence, 1 km of the concrete pavement can fulfill the functional unit. While in the asphalt scenario, $\frac{50}{49}$ of 1 km is required as a reference flow, referring to the functional unit. The system boundaries covering the modeled life cycle stages are detailed for both pavement types in Figure A2.1. Each life cycle stage includes its materials transportation, and a 50-km distance is assigned as a typical case.

2. Life cycle stages

2.1. Materials production

The concrete and asphalt mixture design are selected based on specifications of Quebec conventional materials. This stage also includes raw materials transport from the extraction to the production site. The ecoinvent database v.3.2, which include background processes (e.g., energy supply and raw materials extraction), in addition to infrastructure, is used and adapted to model the materials production stage [1]. For the base and sub-base materials in Quebec, Athena dataset is also used and adapted to the study [2]. The details on the asphalt and concrete mixture designs as well as tie and dowel bars of the concrete scenario are presented in Table A2.1 and A2.2, respectively.

2.2. Pavement construction

Examples of on-site equipment are compactors, pavers, millers, and sealing machines. The data for machinery's fuel consumption comes from its producer catalog (see Table A2.1 and A2.2). For the machines used for joint cutting and sealing, Stripple report used as a proxy [3]. The details of the construction steps including the deployed machinery are also presented in Table A2.1 and A2.2.

2.3. Maintenance and repair

The concrete pavement repair schedule includes joint restoration and surface grinding. Transportation of materials to the site and equipment for the demolition of damaged material as well as resurfacing are also considered at this stage. Based on previous years' experience in Quebec, concrete pavements require a larger mass of salts than in asphalt for de-icing purpose in winter. The salt production and its transportation are considered in this study. An annual application rate of 20 tons per 2–lane km road length is assigned for the asphalt pavement based on earlier works [4, 5]. Because of their light color and higher thermal mass, concrete pavements tend to heat up and cool down more slowly than asphalt. In addition, Concrete pavements are less pervious than asphalt and tend to shed brine more quickly than aged asphalt surfaces, and therefore can be prone to more rapid refreeze than more porous asphalt pavements. The mass of de-icing salts for A difference value of 8.5 t/km.year is set for the concrete scenario for a single carriageway [6]. Details of the maintenance and repair schedules are presented in Table A2.5 and A2.6. The asphalt scenario is majorly repaired by 100 kg/m^2 resurfacing at the age of 14 and 100 kg/m^2 resurfacing at the age of 27, 39 and 49. The repair schedule in concrete scenario includes joint restoration at the age 10 and 19, and the concrete pavement is resurfaced by a 50 mm layer of asphalt after 39 years from construction. The extension and decrease in the pavements lifetime add and removes one repair step in the schedule, respectively. The schedule comes from the average practical possibility of repair that the local transportation government is implementing in this type of road.

2.4. End-of-life

The possible proportion of recycled materials was chosen based on the recent government policy in Quebec [7]. Therefore, their environmental impacts are not considered, and a cut-off approach is selected for the modeling. In this approach, if a material is recycled, the primary producer will not receive any credit for the provision of any recyclable materials [8]. All assumptions corresponding to this end-of-life stage are presented in Table A2.1 and A2.2. It should be noted that in this paper, special attention is paid to the processes that are different between the compared systems. Thus, for the sake of simplicity, all identical processes (in nature and quantities, referring to the presented functional unit - See subsection 2.1) between the two types of pavement are not considered.

Table A2.1. Concrete scenarios input data

Process	Source	Base case	min	max
Concrete lifetime (Years)	Local transportation report [6]	50	39	61
Portland cement mass in concrete (kg/m^3)	Pavement engineering design	332.5	297.5	350
Water mass in concrete (kg/m^3)	Pavement engineering design	140	132	165
Gravel mass in concrete (kg/m^3)	Pavement engineering design	960	960	970
Sand mass in concrete (kg/m^3)	Pavement engineering design	945	945	955
Interground limestone mass (kg/m^3)	Pavement engineering design	17.5	0	52.5
Concrete production in Quebec	ecoinvent v.3.2 [1]	Constant		
Joint restoration	Stripple [3]	Constant		
Concrete sealing machine	Stripple [3]	Constant		
Concrete slip form paver, Wirtgen SP25	Producer catalog [9]	Constant		
Concrete surface milling, Dynapac PL2000	Producer catalog [10]	Constant		
Asphalt overlay thickness used in concrete repair (m)	Local transportation report [6]	0.05	0	0.1
Concrete maintenance salt (kg/year)	Local transportation report [4, 6]	28500		
Percentage of repaired concrete joint (%)	Local transportation report [6]	125	100	150
Concrete rubblization, Badger 8600	Producer catalog [11]	Constant		
Recyclable concrete materials at end of life	Literature [7]	0.5	0	0.6
Dowel bar length (m)	Pavement engineering design	0.46		
Number of dowel bars in one slab	Pavement engineering design	11		
Dowel bar weight per meter length (kg/m)	Pavement engineering design	8.83		
Tie bar Length (m)	Pavement engineering design	0.75		
Tie bar numbers in one slab	Pavement engineering design	6		
Number of Concrete slabs in one km	Pavement engineering design	200		

Table A2.2. Asphalt scenarios input data

Process	**Source**	**Base case**	**Best Case**	**Worst case**
Asphalt lifetime (Years)	Local transportation report	49	39	59
Bitumen mass asphalt (kg/m^3)	Pavement engineering design	125	100	150
Gravel mass asphalt (kg/m^3)	Pavement engineering design	1220	1210	1230
Sand mass in asphalt (kg/m^3)	Pavement engineering design	1140	1120	1150
Base and sub-base materials excavation equipment	Athena report [2]	-		
Bitumen mass in asphalt emulsion (kg/m^3)	Pavement engineering design	Constant		
Emulsifier mass in asphalt emulsion (kg/m^3)	Pavement engineering design	Constant		
Water mass in asphalt emulsion (kg/m^3)	Pavement engineering design	Constant		
Sand in asphalt emulsion (kg/m^3)	Pavement engineering design	Constant		
Asphalt production (at plant)	Pavement engineering design	Constant		
Asphalt paver layer times	Pavement engineering design	2	3	5
Soil compaction, Dynapac CA 151D	Producer catalogue [10]	Constant		
Asphalt compaction, Dynapac CC 122	Producer catalogue [10]	Constant		
Asphalt paver, Dynapac F12	Producer catalog [10]	Constant		
Asphalt surface milling, Wirtgen W 2200	Producer catalog [9]	Constant		
Asphalt thickness used in asphalt repair (m)	Local transportation report [6]	0.14	0.09	0.19
Asphalt repairing number of milling	Local transportation report [6]	4	3	5
Asphalt maintenance salt (kg)	Literature [4]	20000		
Recyclable asphalt materials at end of life	Literature [7]	0.6	0	0.8

Table A2.3. Thickness of asphalt and concrete pavement surface and sub-layers

Pavement type	**Surface layer (mm)**		**Base (mm)**		**Sub-base (mm)**	
	Lanes	**Shoulders**	**Lanes**	**Shoulders**	**Lanes**	**Shoulders**
Asphalt	184	90	281	375	776	776
Concrete	162	150	150	162	929	929

Table A2.4. Materials transportation distance between life cycle stages [6]

Transportation distance to life cycle stages (km)	**Base case**	**Min**	**Max**
production stage	50	20	500
construction stage	50	0	100
maintenance and repair stage	50	20	500
end of life stage	50	20	500

Table A2.5. Repair schedule of concrete pavement [6]

Concrete pavement Process (year of occurrence)
Pavement construction (0)
25% of joint restoration (10)
Restoration of all joints and 25% grinding (19)
100% grinding of the surface layer (29)
Asphalt resurfacing 120 kg/m^2 (39)
Asphalt correction and resurfacing 120 kg/m^2 (49)

Table A2.6. Repair schedule of asphalt pavement [6]

Asphalt pavement Process (year of occurrence)
Pavement construction (0)
Removing a 40-mm layer, Leveling, and resurfacing (14)
Removing a 50-mm layer, Leveling, and resurfacing (27)
Removing a 50-mm layer, Leveling, and resurfacing (39)
Removing a 50-mm layer, Leveling, and resurfacing (49)

2. System boundary

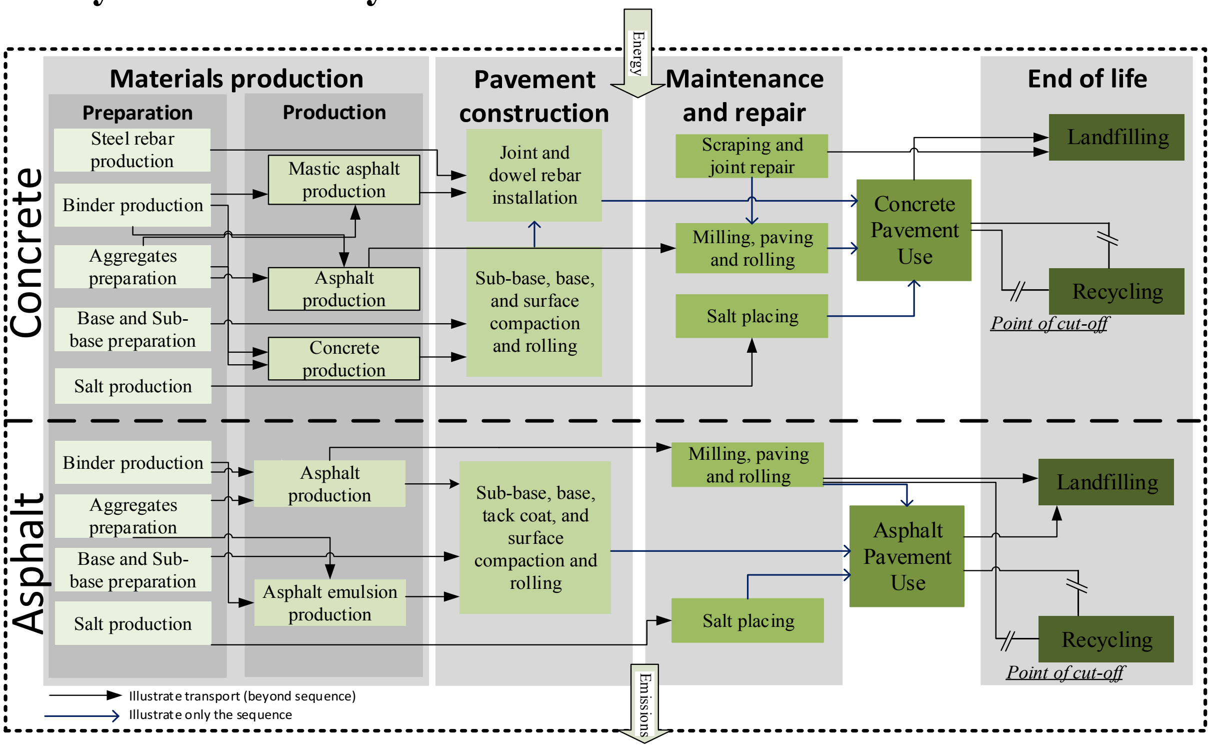


Figure A2.1. Life cycle system boundary of asphalt and concrete scenarios

3. Sensitivity analysis to the life cycle impact assessment (LCIA)

In line with the interpretation phase, a sensitivity analysis is also conducted with using different impact assessment methods. IMPACT 2002+ method is replaced by TRACI V.2.1 to assess the effect of LCIA on the conclusion.

4.1. Uncertainty Modeling in software

In this section, the procedure of analyzing different sources of uncertainty and variability is presented. It is worth mentioning that the same procedure can be applied in the recent version of OpenLCA software with the ecoinvent database. To assess the parameter uncertainty (data quality of environmental flows), the ecoinvent database v. 3.2. was used. In this database, the pedigree matrix has already been implemented to quantify various aspects of uncertainty in the database inventory, such as reliability, completeness, and temporal, geographical and technological correlation of the input data. The parameter uncertainty in foreground processes was also considered in this study. To do so, basic uncertainty was estimated in according to the default values provided by the ecoinvent database [12]. Additional uncertainty factors for completeness, representativeness, geographic, temporal, and technological scope quality of datasets were also included. Quality scores for these factors were ranked based on the proposed pedigree matrix. Table A2.7 shows the details of uncertainty factors for these unit processes. For the rest of the processes, such as those in background, the default uncertainty factors of the ecoinvent database were considered.

In this study, the procedure of assessing the uncertainty and variability sources started from parameter uncertainty analysis. The pedigree matrix is applied in non-aggregated versions (the library name ends with "unit") of the ecoinvent database. In this study, the "ecoinvent, 3 – allocation, recycled content – unit" database was used for parameter uncertainty analysis. It should be noted that all the probability distributions of the parameter uncertainty must be excluded from the simulation when assessing the discrete effect of variability sources and the scenario uncertainty. Therefore, the modeling was performed in "ecoinvent, 3 – allocation, recycled content – system" library. In this library, the pedigree matrix is not included.

Table A2.7. Summary of uncertainty factors in concrete and asphalt foreground systems (in case of difference between asphalt and concrete in the uncertainty factor, the digits in parentheses represents the uncertainty factor for asphalt)

Inventory name	**Indicator Score**					**Basic uncertainty factor**
	Reliability	**Completeness**	**Temporal Representativeness**	**Geographical Representativeness**	**Technological Representativeness**	
Materials for production, maintenance, and repair						
Reinforcing Steel	3	3	5	3	1	0.0006
Concrete ingredients and production						
Sand	1	1	4	2	1	0.0006
Gravel	1	1	4	2	1	0.0006
Water	1	1	4	2	1	0.0006
Cement	1	1	4	3	3	0.0006
Superplasticizer	1	1	3	3	1	0.0006
Limestone	1	1	4	3	3	0.0006
Mastic Asphalt	1	1	4	3	3	0.0006
Asphalt ingredients and production						
bitumen	1	1	2	1	1	0.0006
Sand	1	1	4	2	1	0.0006
Gravel	1	1	4	2	1	0.0006
Asphalt emulsion	1	1	4	3	3	0.0006
Base materials						
Fuels	1	1	4	1	1	0.0006
Electricity	1	1	4	1	1	0.0006
Sub-base materials						
Fuels	1	1	4	1	1	0.0006
Electricity	1	1	4	1	1	0.0006
Construction, repair and maintenance and demolition equipment						
Asphalt paver						
Equipment	1	1	5	5	2	0.3
Diesel	1	1	1	1	2	0.0006
Soil compactor						
Equipment	1	1	5	5	2	0.3
Diesel	1	1	1	1	2	0.0006
Asphalt compactor						
Equipment	1	1	5	5	2	0.3
Diesel	1	1	1	1	2	0.0006

Asphalt paver						
Equipment	1	1	5	5	2	0.3
Diesel	1	1	1	1	2	0.0006
Asphalt miller						
Equipment	1	1	5	5	2	0.3
Diesel	1	1	1	1	2	0.0006
Concrete sealer						
Equipment	1	1	5	5	2	0.3
Diesel	1	1	4	5	2	0.0006
Concrete slip form paver						
Equipment	1	1	5	5	2	0.3
Diesel	1	1	1	1	2	0.0006
Concrete surface miller						
Equipment	1	1	5	5	2	0.3
Diesel	1	1	1	1	2	0.0006
Joint cutter						
Equipment	1	1	5	5	2	0.3
Diesel	1	1	4	5	2	0.0006
Transport	1	1	4	5	2	0.12

The variability sources were defined in the software by defining project parameters in inventory section according to Figure A2.2. Properties of probability distributions, such as standard deviation, and minimum and maximum possible values of the parameters should be quantified in this section. Since we considered equal chances of occurrence for the input and output variables (e.g. ingredients mass of asphalt or concrete mixtures), we assigned a uniform probability distribution and ultimately, a maximum and minimum value for each unit process (see Table A2.1 and A2.2 for the maximum and minimum values).

The scenario uncertainty (herein, allocation methods are defined as the scenarios) was included in the model by defining possible choices. A parameter must be defined in the "parameter section" of project in SimaPro software for definition of the probability distribution of that scenario (in this case, it is defined as "alloc".) According to Figure A2.3, for example, two different unit processes were defined for bitumen supply chain (namely, "Bitumen adhesive compound, hot [QC]| production | Economic allocation" and "Bitumen adhesive compound, hot [QC]| production | Mass allocation". It should be noted that the value assigned to the unit processes were parameterized as "euro_eco" and "euro_mass" in this example.

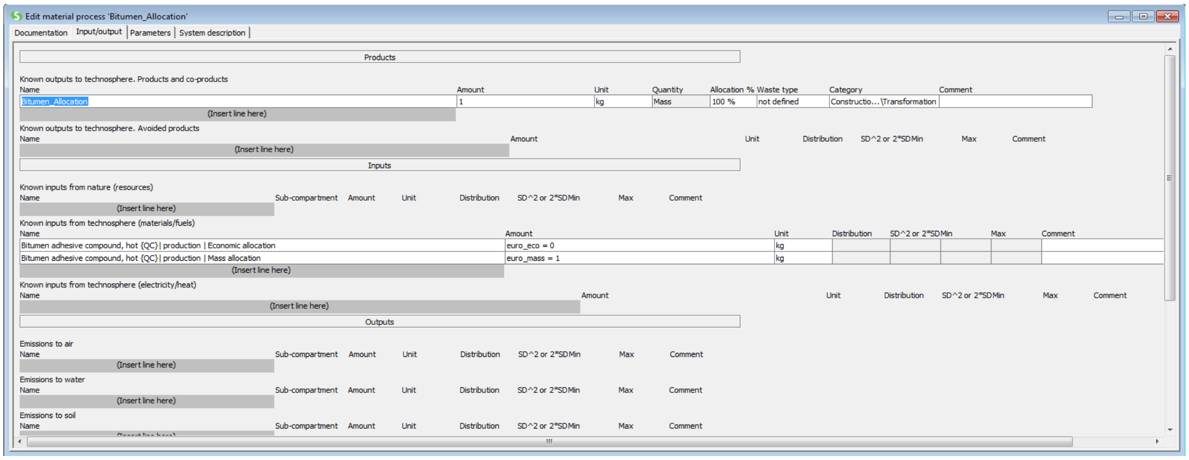


Figure A2.2. New unit processes created for consideration of bitumen allocation choices

These unit processes were then included in a unit process (in this example, “Bitumen_Allocaton”). The value of each parameter was quantified in the “Parameters” tab of the “Bitumen_Allocation” unit process (see Figure A2.4). Instead of defining an absolute value, an equal interval, representing the equal chance of occurrence, was assigned to each scenario. In this example, if the value of 1 ≤ alloc < 2, then the allocation of bitumen refinery (and also all other multi-functional unit processes, such as bitumen extraction and limestone quarry) will be based on mass and if 2 ≤ alloc < 3, the allocation will be based on economic values of the co-products. By determining a uniform distribution and setting the minimum and maximum value of 1 and 3 for “alloc”, we reach to a discrete uniform distribution for this parameter, which enables us to include the allocation choices in the scenario uncertainty analysis.

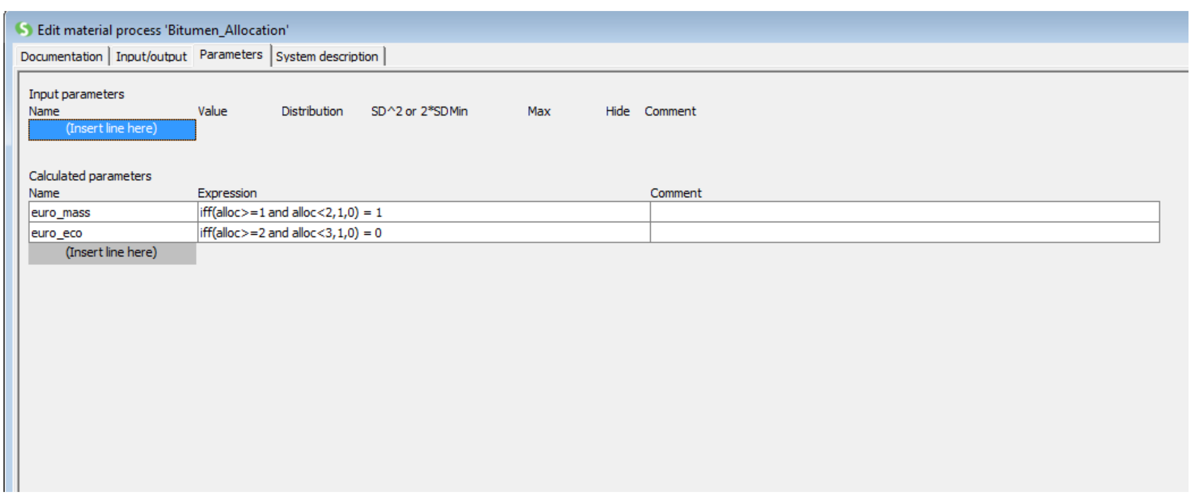


Figure A2.3. Quantification of parameters in scenario uncertainty using intervals

4. Results

5.1. Contribution analysis of midpoint results (IMPACT 2002+)

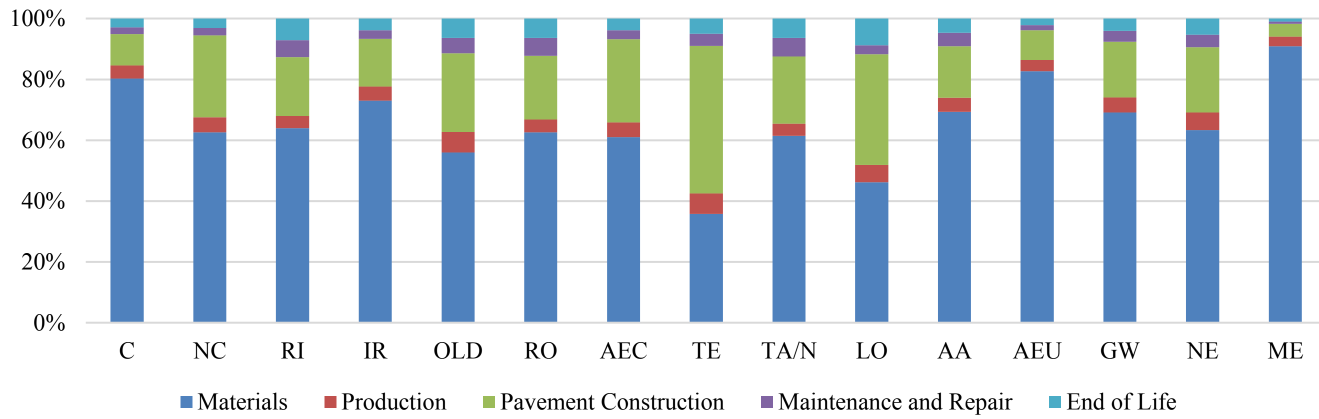


Figure A2.4. Midpoint contribution analysis of concrete pavement modeled based on 5 life cycle stages (IMPACT 2002+) [Carcinogenic (C), Non-carcinogenic (NC), Respiratory inorganics (RI), Ionizing radiation (IR), Ozone layer depletion (OLD), Respiratory organics (RO), Aquatic ecotoxicity (AEC), Terrestrial ecotoxicity (TE), Terrestrial acidification/nutrification (TA/N), Land occupation (LO), Aquatic acidification (AA), Aquatic eutrophication (AEU), Global warming (GW), Non-renewable energy (NE), and Mineral extraction (ME)]

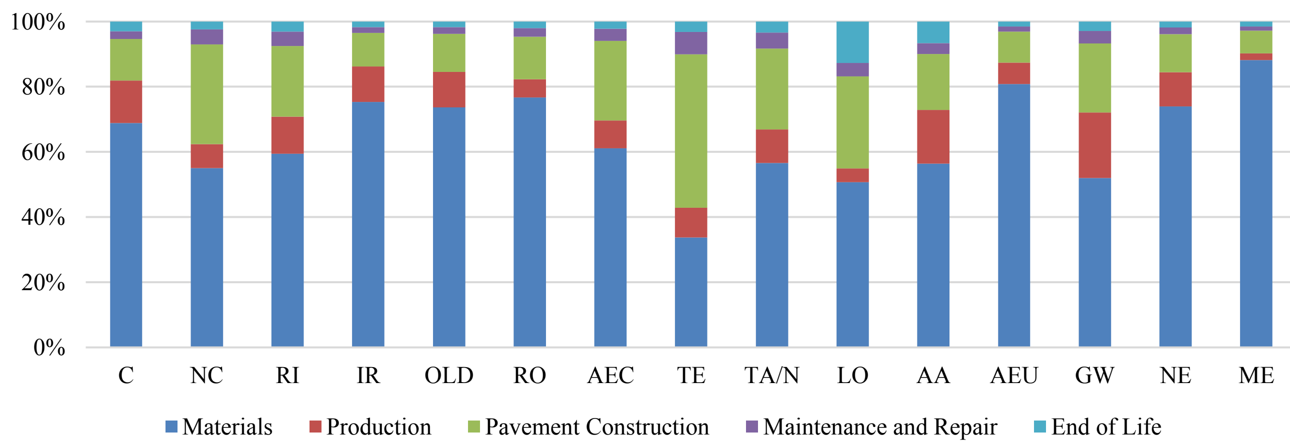


Figure A2.5. Midpoint contribution analysis of asphalt pavement modeled based on 5 life cycle stages (IMPACT 2002+) [Carcinogenic (C), Non-carcinogenic (NC), Respiratory inorganics (RI), Ionizing radiation (IR), Ozone layer depletion (OLD), Respiratory organics (RO), Aquatic ecotoxicity (AEC), Terrestrial ecotoxicity (TE), Terrestrial acidification/nutrification (TA/N), Land occupation (LO), Aquatic acidification (AA), Aquatic eutrophication (AEU), Global warming (GW), Non-renewable energy (NE), and Mineral extraction (ME)]

5.2. Consideration of maintenance materials, machinery, and transportation as a life cycle stage

All presented results are consistent with the defined system boundaries, which the materials production is considered as a single life cycle stage feeding pavements construction and their maintenance and repair. One question arises on what the changes to the contribution analysis results will be (i.e. Figure 4.2 and 4.3) if we consider all the maintenance and repair corresponding materials, transportation, and machinery as a distinct life cycle stage (i.e. not aggregated with materials production stage). The obtained results show that there is no significant change in the main contributor except for the resources category. As shown in Figure A2.4, concrete pavement resurfacing with asphalt materials (as a part of repair materials) is the reason behind the observed shift. In the asphalt scenario, the accumulated thickness of the asphalt used in repair is slightly more than the initial construction. Hence, the main contributor of resources category in the asphalt scenario is both the materials production for initial construction and maintenance and repair.

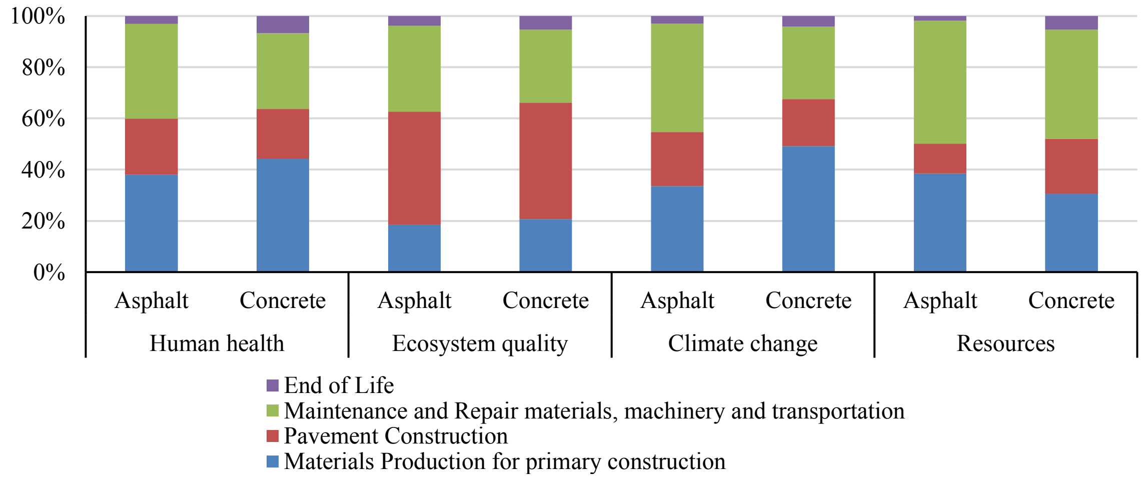


Figure A2.6. Consideration of maintenance materials, machinery, and transportation as a life cycle stage

5.3. Contribution analysis of midpoint results (TRACI V.2.1)

To assess the robustness of the midpoint results (Figure 4.2), a sensitivity analysis is performed with using TRACI LCIA method. Spatially differentiated environmental effect chains are modeled by TRACI and IMPACT 2002+ method. In TRACI, the characterization factors are developed for the North American condition, while for IMPACT 2002+ includes European context. As shown in Figure A2.5, a significant difference is highlighted when assessing the contribution of the end-of-life stage. In the asphalt scenario, eutrophication is dominated by the end-of-life stage. Landfilling of asphalt releases a substantial amount of COD (1019 kg N_{eq}) majorly from bitumen leaching in long-term, which leads to 44.2% contribution in the eutrophication category.

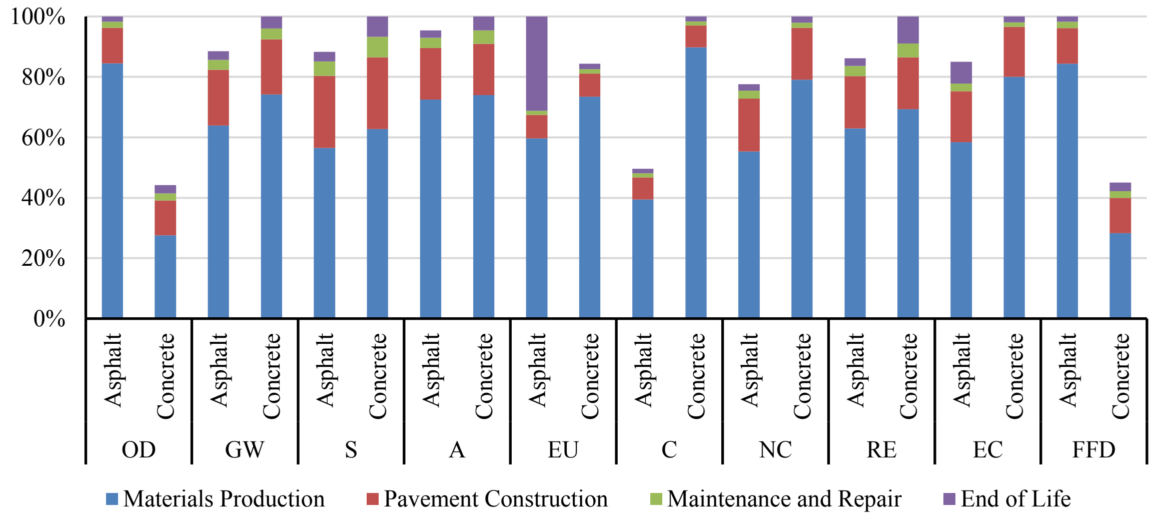


Figure A2.7. Midpoint results of concrete and asphalt scenario (TRACI V.2.1) [Ozone depletion (OD), Global warming (GW), Smog (S), Acidification (A), Eutrophication (EU), Carcinogenic (C), Non-carcinogenic (NC), Respiratory effects (RE), Ecotoxicity (EC), Fossil fuel depletion (FFD)

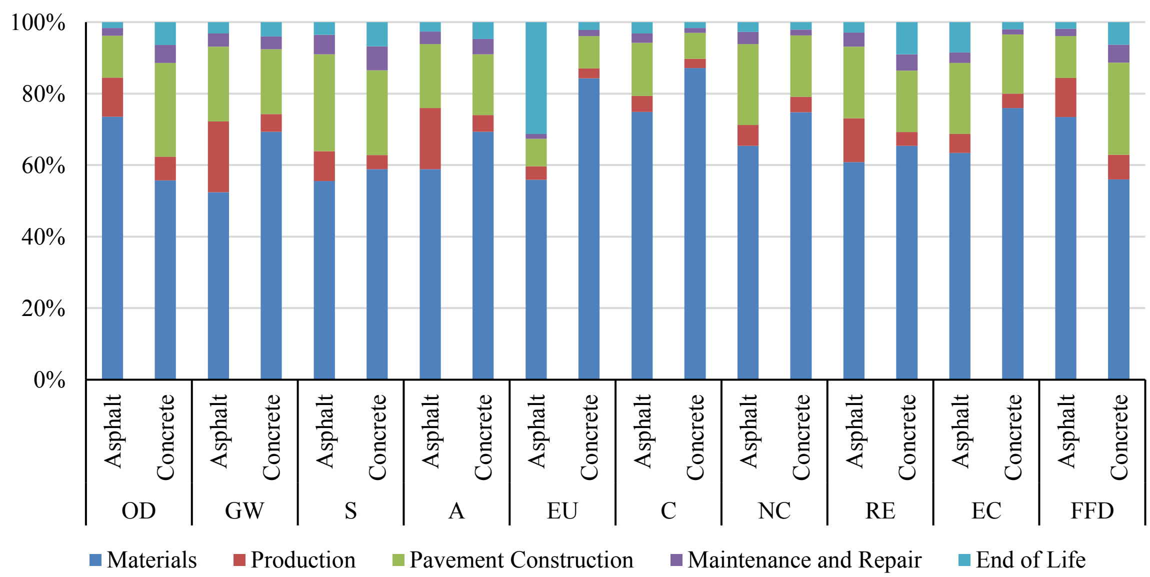


Figure A2.8. Contribution analysis of asphalt and concrete pavements modeled based on 5 life cycle stages (TRACI V.2.1) [Ozone depletion (OD), Global warming (GW), Smog (S), Acidification (A), Eutrophication (EU), Carcinogenic (C), Non-carcinogenic (NC), Respiratory effects (RE), Ecotoxicity (EC), Fossil fuel depletion (FFD)]

5.4. **Contribution of midpoint categories in the endpoint results in IMPACT 2002+ [13]**

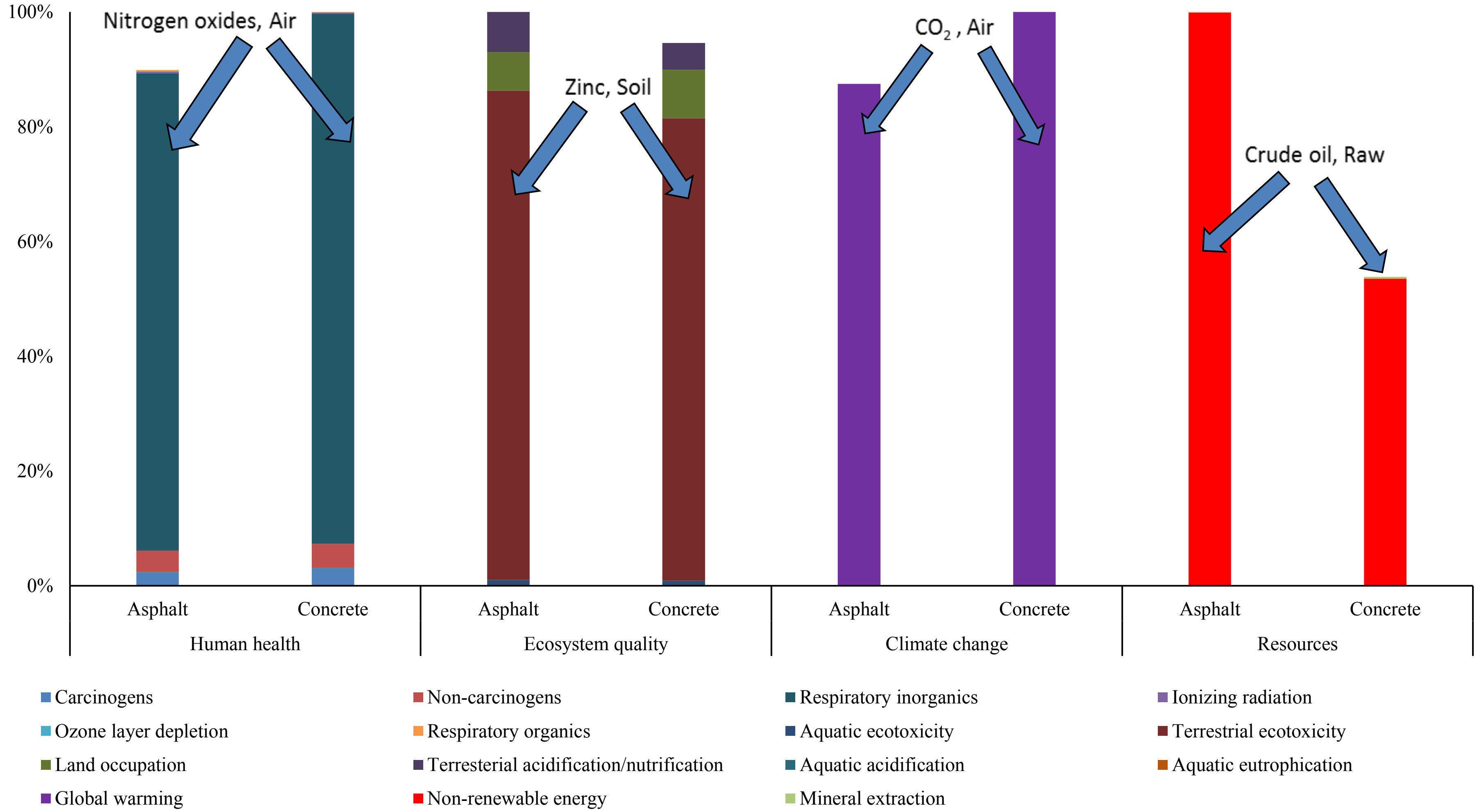
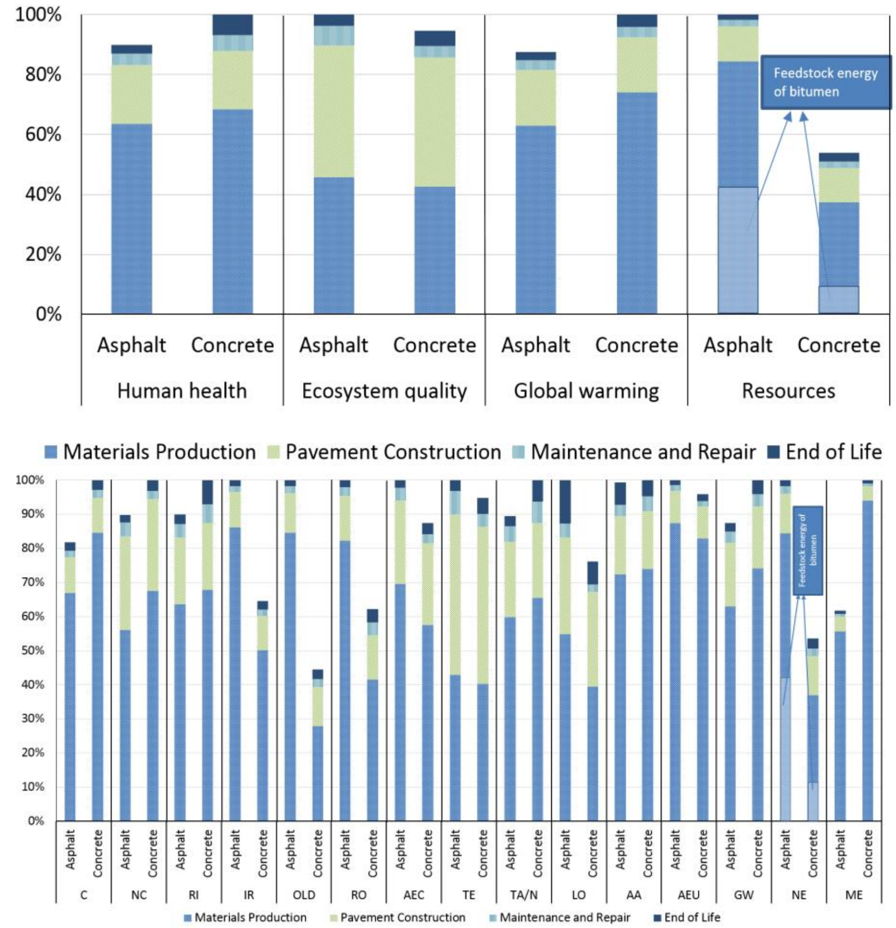


Figure A2.9. Contribution analysis of midpoints in endpoint categories



a)

b)

Figure A2.10. Contribution of bitumen feedstock energy in a) endpoint and b) midpoint results

5.5. **Consequential results of the case study**

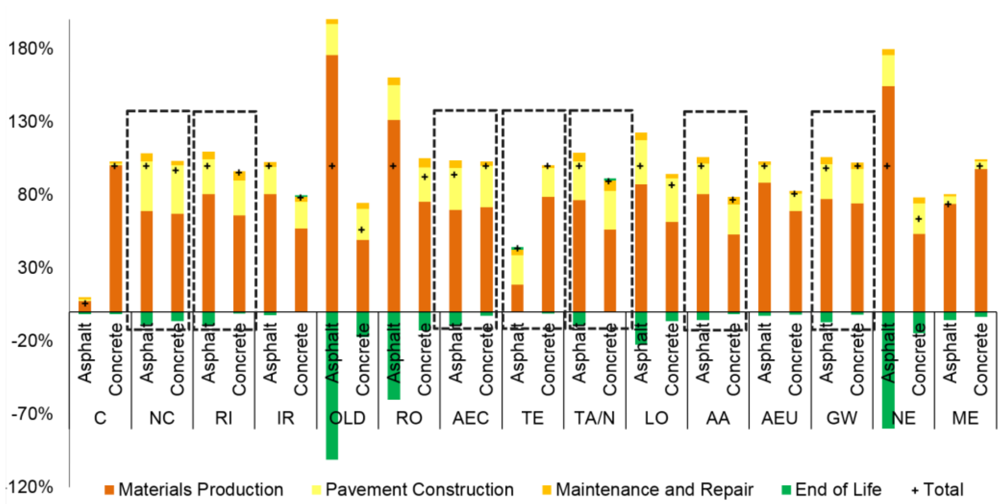


Figure A2.11. Consequential midpoint results of the case study (the categories whom the conclusion is changed are squared by dash line)

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Appendix 3.

Supporting information for Removing shadows from consequential LCA through a time-dependent modeling approach: application to policy-making in road pavement sector

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1. Modeling details

1.1. Goal and Scope and functional unit definition

The purpose of this study is to evaluate the environmental impacts of increasing the use of concrete pavement as an alternative (ALT) instead of the business-as-usual (BAU) case, herein asphalt pavement. For this purpose, this paper is intended for decision support in a situation where the product (concrete pavement) is selected as an alternative for construction of new pavements in Quebec. The obtained results can provide a decision support in situations where governments consider to locally increase the use of concrete pavement in new road construction projects. It is worthy to mention that this study only includes "small changes" for different resources used in the life cycle of pavement, which changes in their demand will not alter the overall trend in the market. The functional unit of this study is "providing traffic service over the whole length of two-lane road with 20,000±1,000 AADT, including 5% truck, for a 50-year lifespan, in Quebec urban area with 20,000 AADT, including 5% truck, for a 50-year lifespan". This functional unit comprises 287.2 km of Quebec roads according to the MTQ statistics. All these road surfaces are currently covered by asphalt (BAU scenario) and the reconstruction of all the road length is assumed to occur during one year in different regions of the province of Quebec. The consequences of the changes in construction material demands for this decision are assumed linearly. For example, a rough estimation for this FU size reflects 174,000 t of increase in cement demand while the production capacity of Quebec is in the order of ten million t. Therefore, the demand change for cement cannot affect the overall market situation, and therefore could not bring into play new markets or new products and technologies. The baseline year of this case study is considered as 2018, when the construction of the pavements is initiated.

1.2. Life cycle stages and time horizons

When analyzing the market in CLCA studies, the focus will be on the supply of the product system and how the change in the demand will affect this supply. All the life cycle stages of a pavement are characterized by different types of construction materials, such as cement (binder material for rigid pavement), aggregates, steel, bituminous materials (binder material for flexible pavement), and water. The thickness of pavement layers in cold regions, such as Quebec, are significantly greater than those in mild weather regions to satisfy freezing depth and traffic service. Consequently, a considerable volume of the materials must be transported from raw materials manufacturers to plant or to the construction site. Due to the large volume of the required materials, it is important to limit the transportation distance, hence reduce the construction cost and environmental impact. In fact, the market for products with a low value to weight ratio tends to be local [1]. Steel can be considered as an exception, which has a global market size since a major part of steel consumed in Canada is imported from the U.S. and China [2]. For the rest of materials, local and regional market are considered in the modeling. The systems are modeled from cradle to grave in this study. The pavement product system includes five different stages, including materials production, pavement construction, pavement use, maintenance and repair, and end-of-life. The BAU lifespan of 49 years is considered, assuming a certain number of resurfacing to maintain the serviceability. Similarly, the ALT pavement lifespan is 49 years, but a layer of bituminous asphalt will be used to resurface the concrete pavement after 38 years of age.

A. Materials production: This stage includes the production processes of the materials used for the construction of pavement layers, from raw materials extraction to their transformation into the final product. According to Weidema, individual demands of different sectors of consumers imply that capacity adjustments should be seen as a continuous process, and therefore these decisions affect the current and expected trends in the market volume [3]. However, in the case of pavement materials for new construction and for the functional unit used in this study, short-term changes in demand for the materials are not continuous. In fact, there is no regulated shape of consumption for the selected pavement construction with the specified traffic level. As a result, there is no implication of continuous demand for the required investments. Indeed, in the case of pavement construction, market situation of the materials has little influence on capacity adjustments considering significant production capacity and long-life cycle of the infrastructures for the materials production [4]. For example, for the new construction of pavements, the change in material's demand may not require a new capacity installation. It should be noted that long-term affected suppliers can provide parts of construction materials implemented for repair stage since the government may possibly predict the required repair materials that are procured in the next 5-10 years.

B. Pavement construction: All the execution phases of surfaces and the sub-layers construction, including equipment fuel, consumption and their resulting emissions to the environment are considered and analyzed at this stage.

C. Maintenance and repair (M&R): These tasks are essential for recovering functionality of the pavements over their lifespan period. The repair schedule of the pavements is necessary to restore the value of the pavement, including surface roughness and albedo in the use stage. The equipment required in this stage are considered as the 15^{th} years of the service. Therefore, adequate anticipation for the capacity increase will be considered to supply this demand. Details of tasks and their corresponding quantity are shown in Table A3.1. The lifespan of the pavements is considered to vary as a consequence external criterion such as premature failure in materials (e.g., low quality of placement during construction and maintenance can result in premature deterioration due to cold or hot weather or severe winter [61]). This variation comes with a repair schedule to maintain the serviceability of the structure.

Table A3.1. Repair schedule of ALT and BAU pavement scenarios

Concrete pavement Process (year of occurrence)	**Asphalt pavement Process (year of occurrence)**
Pavement construction (0)	Pavement construction (1)
25% of joint restoration (10)	Removing a 40-mm layer, leveling, and resurfacing (15)
Restoration of all joints and 25% grinding (20)	Removing a 50-mm layer, leveling, and resurfacing (28)
100% grinding of the surface layer (30)	Removing a 50-mm layer, leveling, and resurfacing (40)
Asphalt resurfacing (a 50-mm layer) (40)	-

D. Use stage: This stage includes emissions that are due to the use of pavement during its service life. Extra car fuel consumption induced by surface roughness and structural rigidity of pavements, albedo effect of pavement as a result of radiative forcing intensification and urban heat island effect, lighting energy for road illumination are included in this stage, in addition, in ALT scenario, concrete carbonation was considered. To assign the appropriate time horizon for the stage, the following consideration was consistently applied to the model:
Unlike the materials production stage, the accumulated demand of fuels and electricity result in an installation (when there is an increase in demand) or phasing out (when there is a reduction in the demand), which are the basis for decisions on capital investment [3]. Indeed, due to the long-lifetime (after 5 or 10 years of service), there is a potential of installing new supplying capacity because of the accumulated change in demand. Therefore, this part of demand changes in the use stage over time is supplied by the new installed capacity (i.e. the long-term affected technology). Nevertheless, the supply and the demand during the short-term period (e.g. the first 5 or 10 years of service life) are covered by the existing capacity.
E. End-of-life: This stage refers to materials recycling and landfilling. The main processes related to this stage are demolition and transportation of waste, equipment fuels consumption and emissions, as well as waste landfilling and managing avoided recycling impacts. A proportion of demolished materials is recyclable, which will influence the market for virgin construction materials. It is well anticipated that the pavement materials can be recycled at the end-of-life in advance. Therefore, this substitution involves only long-term effects, i.e. effects from installation and production on newly installed capacity. All the recycled materials recovered in this stage are replaced by the materials produced in long-term (50 years after the construction stage) and therefore induce a change in the capacity adjustment including long-term affected suppliers.

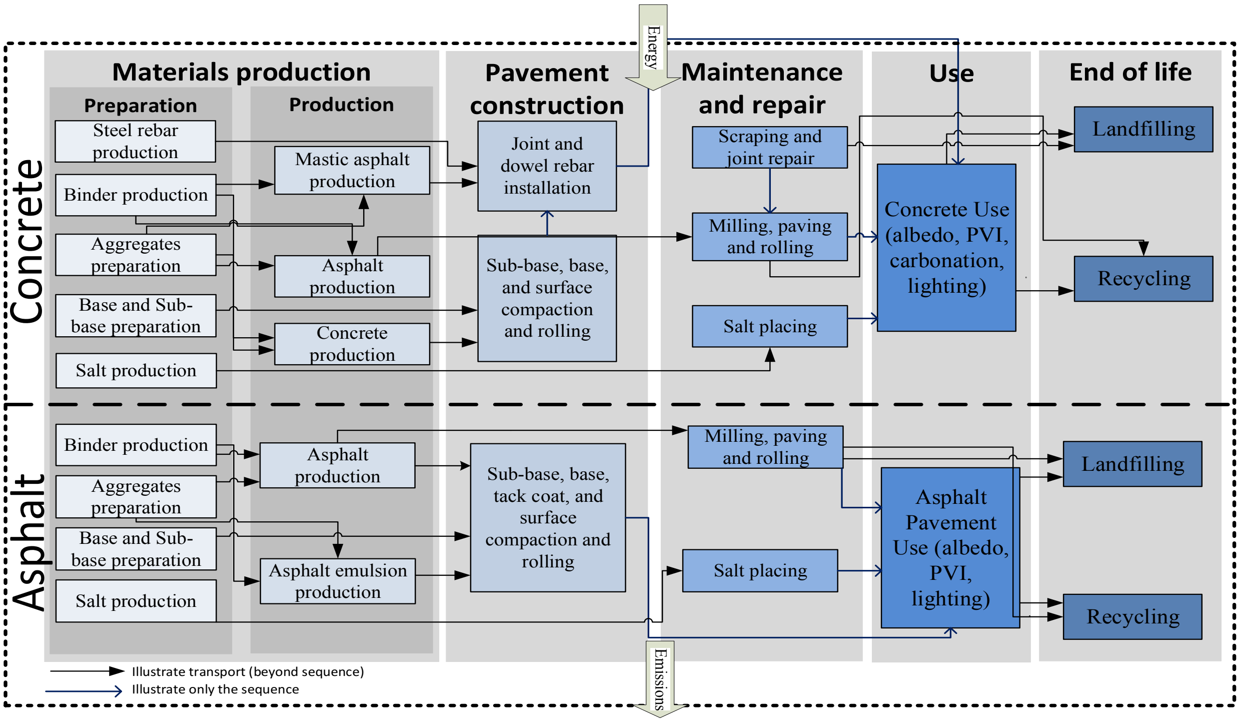

Figure A3.1. Life cycle system boundary of asphalt and concrete scenarios (PVI stands for pavement-vehicle interaction)

2. Procedure for identifying short-term and long-term affected technologies

Once a recent technology is installed, further changes in short-term demand will still affect the older technology, because this latter is often the costliest to run. It is important to understand that even though the short-term fluctuation constantly will affect the older technology in the short-term, it is the accumulated changes in the short-term demands that make up the long-term changes, which eventually lead to the installation of the new machinery. The long-term effect of the demand is, therefore, the additional exchanges from the newly installed technology.

Various researchers explained the fundamentals of consequential modeling. According to Weidema [5], it is the change in demand for the studied product that is modeled in consequential framework. A cause and effect relationship between the change in demand and the related changes in supply is generally investigated. In fact, the studied product is produced by an additional capacity in the case of an increasing trend in the market. This additional production capacity must come from unconstrained suppliers. Allocation problems are always dealt with using system expansion [6], which is also a priority in allocation approach of ISO 14044 [7]. The procedure of identifying the affected technology is performed using the step-wise procedure proposed by Weidema et al. [8]. This procedure considers in the first step the time horizon of the consequences in which changes happen (short and long-term) followed by the determination of the markets affected by the changes. The second step consists of identifying the markets trend and the products constraints. In the last step, the most sensitive process to change the demand is determined and applied to the model as the affected technology. In the case of an increasing or steady market, the affected technology is the unconstrained one with the lowest long-term production cost. On the other hand, the highest short-term cost technology is the affected one when the market trend is rapidly decreasing [6].

An important aspect of the end of life stage is the modeling of avoided environmental burdens from recovered and re-used waste for different construction materials. There are certain exceptional examples of stable and mature market for recycled products, such as pozzolanic materials for concrete production. Nevertheless, these materials belong to a constrained resource and therefore cannot be the affected supply to a demand-driven market that has other unconstrained suppliers [6]. Recyclable materials with a high demand belong to mature markets (i.e. where supply matches demand) in which all the recycled material is already consumed. Under this condition, the increase in demand for recycled materials cannot be fulfilled [3]. For example, the markets for pozzolanic materials are mature, i.e. nearly 30-50% of the pozzolanic materials obtained from by-products at present globally is already in use [9].

2.1. Affected technology in foreground system

a) Concrete manufacturing

The statistical data is obtained from various sources, such as Statistics Canada and IBISWorld [10, 11]. Concrete ready-mixed industry in Canada involves a steady growth of 2.5% in recent five years according to IBISWorld report [10]. This growth is predicted to continue at the rate of 1.6% in the next five years benefitting from improved facilities and construction of transport infrastructure. The technology of concrete production in Quebec focuses on wet mix type plants, where water is mixed with cement and aggregates in the plant rather than introducing water in the truck mixer. Since more than 75% of the concrete production cost comes from materials procurement [11], less attention is paid to the technological development and optimization of the cost in ready-mix plants [12]. Hence, the distance from the plant to the construction site may be the key factor in the price adjustment of the manufactured concrete. We considered the nearest plant to the construction site as the long-term affected technology accordingly. For the short-term effect of a change in ready mixed concrete production, the ready-mix plant with farthest transportation distance to the understudied urban area is selected as the supplier with the highest short-term cost.

b) Cement manufacturing

In 2009, Canadian cement manufacturers exported more than 3.4 Mt of cement and clinker to the U.S., which is approximately one-third of Canadian production [13]. During 2010, cement manufacturers produced over 12.4 Mt of cement. Canada exports more than 30% of its total production, mainly to the U.S. The major Canadian cement import comes from Asia for Western Canada (around 20% of the whole consumption), and the central parts, such as Manitoba, are fed by suppliers from Montana, the U.S. However, this practice does not affect the cement market in Quebec [14]. As can be observed in Figure A3.2, since the post-financial crisis era in 2008, cement production and consumption have been dramatically raised. The consumption data consistently omits cement made or imported by the nonparticipating sellers in the survey by Statistics Canada. The exact value of the omitted amount is not specified, but it may include up to 12% of domestic consumption in Quebec and up to 3% of total consumption in Canada [13].

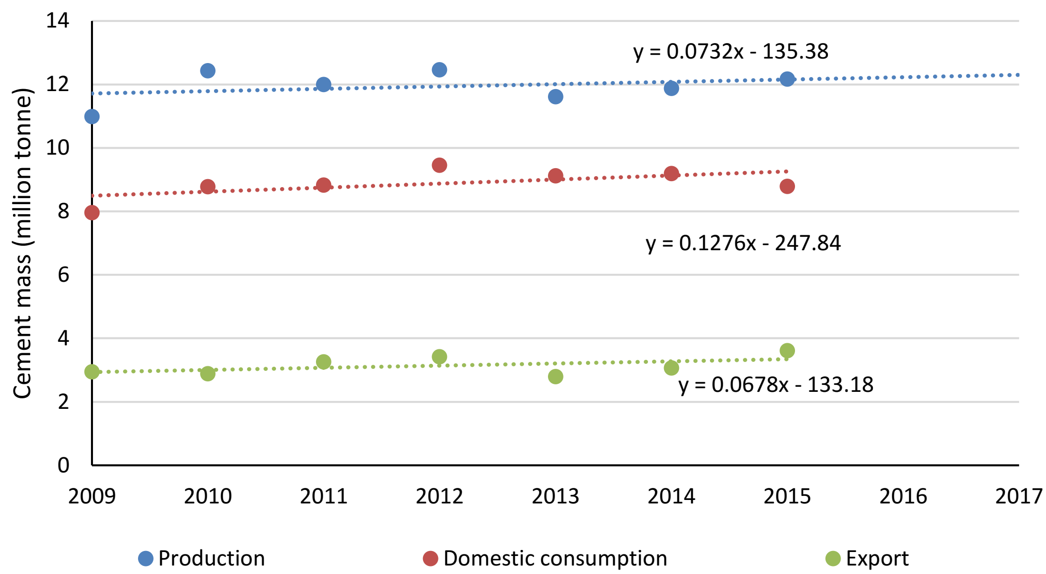

Figure A3.2. Cement production, domestic consumption, and export in Canada (Adopted from Statistics Canada [13, 15] and IBISWorld [14])

The current production capacity of cement plants in Quebec are 3.9 Mt per year and only 1.9 Mt is consumed in Quebec [13, 15]. Considering the average percentage of export to the U.S. from Canada (29.7% of the total production according to Figure A3.2), around 70.3% of the current production capacity is consumed locally. Considering the effects of a marginal increase in cement production, the short-term scenario focuses on one of the existing cement manufacturers, while in the long-term scenario, the new supplier will probably be installed in later years, which will be the affected one. Current cement manufacturers in Quebec are supplying the demand for different technologies (Lafarge, CRH, Ciment Quebec, or Colacem plants). For the short-term affected technology, the oldest technology (dry kiln) operating in Quebec [16] with the longest transport distance is selected, because it is the costly system to run.

It should be noted that the cap-and-trade system regulated in 2013 forced various industrial sectors that are intensively emitting greenhouse gases (GHGs) to upgrade to less emitting facilities [17]. Otherwise, they are mandated to purchase credits to make up for more GHGs than the 25,000 t [18]. These regulations can increase the price of the cement produced by older technologies, such as dry kiln process since their fuel combustion for cement production emits a significant volume of GHGs (0.39 t/t clinker for steam coal) [4]. An increase (from \$16.4 to \$18.08 per tonne of CO_{2eq} in 2020) in a carbon tax of Quebec will be the evidence of an increase in cement production cost with older technologies that emit a higher quantity of GHGs rather than the recent ones with preheater and precalciner. As a result, it would be a political constraint on the suppliers with the older technologies in the long-term frame. It cannot be feasible to predict construction of a new cement plant in a region unless the investments and the plan have been drawn for a long time, because the plant construction cost has a very long payback period. However, a new supplier (e.g. new cement plant) is likely to be available to cover the additional demand of the region. In Quebec, it is announced from the early 2000s than the next cement plant that is going to supply the demand is McInnis aiming to produce 2.2 Mt per year. The new plant is claimed to consume 3,100 MJ/t of clinker and overall consumption will be less than 90 kWh/t of cement produced. The used technology will reduce the energy for clinker production by up to 29% compared to the dry kiln [4].

c) Fuel for clinker production

The affected fuel for clinker production can be the fuel between coal, gas, oil (e.g. residual/heavy fuel oil), and alternative sources, such as waste tires and biomass [16]. With respect to identifying the affected fuel, primary data sources are used to determine the production cost. There are different grades of coal as fuels, which are distinguished by their carbon content. The higher carbon content will correspond to the higher quality. In the cement industry, steam coal is mainly used to cover the heat combustion for calcination. Although the coal market trend in Canada due to policy is a constraint, natural gas expansion, which induces a slowing export intensely, is decreasing by 15% [19]. Its cost is still one of the most competitive ones according to Figure A3.3. There is not any coal mine in Quebec and only 1% of the total energy consumed in industrial section (equivalent to 23 PJ) comes from coal, which is supplied by Central Appalachian mines, such as those in New York and Pennsylvania in the U.S. The marginal price of the coal is determined by the aggregation of coal production and the transportation to Quebec.

The use of heavy fuel oils is substantially decreasing due to the recent banning policy of Quebec government on the fuel with high sulfur content [20]. Natural gas, tire-derived fuels (TDFs), and biomass are increasingly used in this industrial sector. Since 1993, the Quebec government has implemented several programs to stimulate the recovery, recycling, and recovery of used tires in Quebec [21]. For the short-term supplier, the natural gas as the affected supplier by the change in clinker fuel demand is considered. The plant corresponding to the long-term affected supply of cement signed a cooperative agreement of using forest biomass as an auxiliary fuel, which is the first alternative for the cement plant and constitutes a fuel source in abundant supply in the region. The source of biomass is located in St-Elzéar with a distance of 100 km to the plant. The produced biomass is the residue of wood processing (bark, sawdust and shavings, trim ends, edgings, etc.) or slash (branches, needles, leaves, etc.). The amount of biomass produced in this area is constrained by the volume of determining co-product (i.e. timber) since it contributes little to the total revenues of the corresponding unit process (e.g. sawmill). However, in Quebec, there are political targets for 2030 and beyond in place to increase the proportion of biomass, which will contribute to developing a market for biomass in long-term [22]. Therefore, the biomass is considered as the unconstrained product for the calcination process.

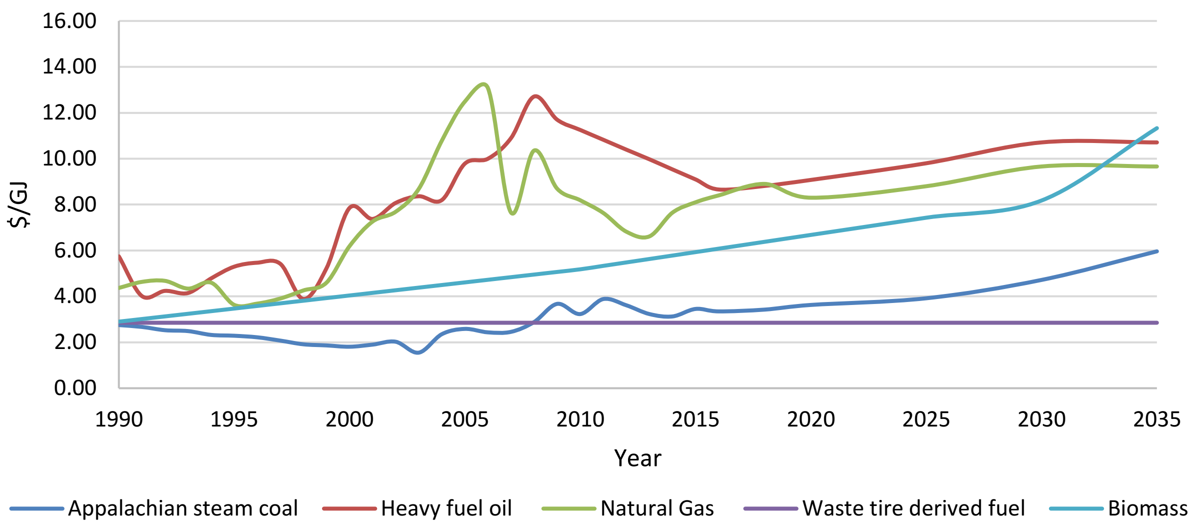

Figure A3.3. Historical and forecasted cost of different fuels (Biomass [23], Coal [24, 25], Natural gas [26, 27], Waste tire derive fuel [28], and heavy fuel oil [29, 30]) for clinker production (Note: currency is expressed in $ Cdn and are in the base year 2015. Conversion between Canadian and US dollar, where required, has been done at the rate of $1 US = $1.32 Cdn.) The energy content of fuels for clinker production is extracted from different sources [23, 31] and the emissions from fuel combustion are obtained from [32] and [33], respectively.

d) Aggregates manufacturing

Although aggregates (sand and coarse aggregate) are the cheapest solid materials of the mixtures (approximately $20/t aggregate versus $140/t of cement), it is required to have their significant volume to manufacture the concrete and asphalt pavements. Hence, due to this low price to mass ratio, the aggregate's market similar to the ready-mixed industry is highly dependent on the local suppliers. For nearly 15 years, the sand and coarse aggregate production are quite stable in Quebec and about 300 manufacturers, spread over the whole territory, produce an average of 30.0 Mt per year [34]. The major application of sand and coarse aggregate in Quebec (55%) is in the road construction and maintenance [34]. There are more than 300 aggregates mines in Quebec and various projects supply their demand majorly from the nearest mine to minimize the final cost of the aggregates. Another parameter, which influences the price and the application of the aggregates, is their type (texture). Particularly, in concrete mixtures, the shape of sand particles plays an important role in the cement content of concrete to satisfy specific workability and targeted hardened properties. Generally, natural sands are being used in conventional and high-performance concrete mixtures, since less quantity of aggregates are required to achieve desired workability and mechanical properties of the mixture compared to those with crushed sands. As a result of using crushed sand instead of natural sand, water demand will increase by 6 to 9 kg/m^3 and the sand content by 2 to 3% in the mixtures [35]. As a consequence of the increase in water content and considering a constant water-to-cement ratio, the relative increase in cement content is required.

Assuming the full operation of the preferred suppliers, i.e., the natural sand, in the short-term, the affected supplier of the sands for concrete demand changes is crushed sand since it is the unconstrained in the sand market. On the one hand, the natural sand production is limited to the areas near rivers. The increasing difficulty in sand extraction from rivers has a negative effect on the bottom line for many mines. On the other hand, asphalt producers prefer asphalt mixture of crushed and natural aggregates since the crushed sand is cheaper (due to its abundance and simple manufacturing process) and the infrastructure for its production can be installed in almost every projects site owning an appropriate area.

Although generally abundant, sand and coarse aggregate still constitute less for most parts of southern Quebec a limited and non-renewable resource whose exploitation is often reduced to restricted areas. For example, the Montreal manufacturers, representing almost half the population of Quebec, consumes half of the aggregates production of the province, while its resources in the sand and coarse aggregate are limited. Depleting natural sand and strict environmental regulations on mining (as two constraints for natural sand manufacturing) gradually shifts the attention towards an alternative for fine aggregate. Therefore, crushed sand will be available to produce a concrete mixture and therefore is the long-term affected technology. Considering the use of crushed sand in the mixture, an increase in the concrete matrix phase (sand content by 2.5% and water and cement content by 7.5 kg/m^3) and, consequently, reduction in gravel content is applied to the mixture.

e) Water supply

Similar to other concrete ingredients, water consumption is growing in Quebec. Supplying a qualified water for concrete production in Quebec is not a big deal since this area has fresh water and the water is plentiful. Most of the batching plants supply their own needs by means of different wells in the batching site. It is also conventional to use the water that has been already used for washing aggregates and truck mixers in a concrete plant. The used water is a by-product of the aggregate and mixers washing and its content is dependent on the determining co-products (washed aggregates and cleaned mixers). Therefore, the recycled water cannot supply the increase in water demand. Short-term and long-term affected technology for water supply is the only remained supplier, which is a water well in batching plant.

f) Chemical admixtures

The role of chemical admixtures in concrete production is inevitable in this century to improve the properties and durability of concrete. Besides, different chemical admixtures are part of the conventional ingredients of the structural concrete mixtures produced in Canada. However, no historical data is available for supply and demand of these admixtures in Canada. In addition, the market trend is concrete manufacturing is moderately increasing (2.5% growth). As a result, it is expected that the chemical admixtures market poses an increasing demand similar to the U.S and other parts of the world [36, 37]. The application of these admixtures (e.g. superplasticizers, air entraining agents, etc.) aims to modify and improving properties of concrete. The short-term effect of an increase in demand of superplasticizer is on the oldest technology of superplasticizer, namely lignosulfonate-based admixtures, which is required in greater quantity due to the lower efficiency compared to other admixtures. The average dosage used in the concrete mixture is assumed 1.5%, by mass of binder. The most preferred technique is the lately developed Polycarboxylate based superplasticizer, which performs better in enhancing fresh and hardened properties of concrete. Its typical content is less than 0.5%, by mass of cementitious materials mass, for conventional concrete. The inventory for the chemical admixtures was obtained from the UK chemical admixture association [37].

g) Steel rebar manufacturing

The reinforcing rebar supply chain can be divided into two markets, including the production of crude steel and manufacturing rebars from crude steel. An increasing trend in reinforcing rebars, both in production and consumption, is observed in recent five years (1.7%). This increase is expected to continue in the far future [38]. In Fact, future of the rebars highly depends on the construction industry, since this sector consumes all the products. There will be a significant increase in non-residential construction, from 2014-2024, more than 47,000 projects are aimed to build in the form of different infrastructures such as bridges, subways, and rails [39]. In addition, in 2016, the government announced an increase in spending on infrastructure projects over the next five years; an estimated $60 billion of new investment over the next 10 years, including an additional $10 billion over the next two years.

Two main steel manufacturing technologies have been supplying the demand in the world, namely electric arc furnace (EAF) and blast oxygen furnace (BOF). The EAF consumes the majority of scrap steel in the market. Steel scrap is a fully utilized by-product and is not the determining co-products in its production process. Therefore, production of steel by this technology cannot affect the output from plants that use scrap steel and is technologically constrained [40]. So far, the largest geological source of iron in Canada is the Labrador Trough in the adjacent of Labrador province and northern Quebec. These provinces account for virtually all the iron ore mine in Canada. According to Figure A3.4, although the steel demand is increasing, the local production has been decreased since 2010 and the government is forced to import the remainder. In fact, protectionist legislation and dramatic increase of foreign imports resulted in a significant drop of exports (-6.1%), while imports recorded an unprecedented growth of 16.4% in 2014-2015 [43, 44]. The rebars produced with BOF technology that are imported from Germany has the highest short-term cost between the existing suppliers [45] and, therefore, is the short-term affected supplier.

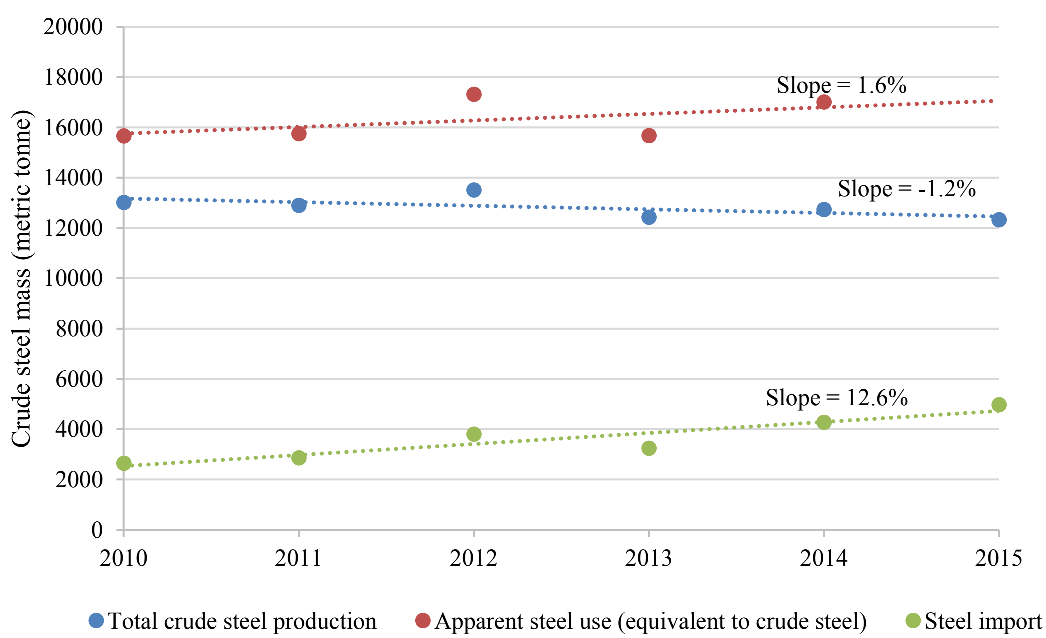

Figure A3.4. Historical statistics for steel demand and supply in Canada [41, 42]

The import price of rebars in some cases (particularly from China) is lower than other suppliers, even from that produced in Canada [46]. However, the Canadian International Trade Tribunal's new policies on anti-dumping and subsidizing will act as a political constraint on additional import to improve the local market [47]. The long-term affected supplier of rebars is, therefore, the nearest local supplier inside Canada with the highest technology. In the prospective scenario, according to Weidema [40] and Morfeldt et al. [48], the affected technology can be changed by the considered time interval. The affected technology later than 2040 is expected to be "blast furnace with carbon capture and storage and top gas recycling" since it is the newest technology supplier that is going to be developed in future to cover the demand in the corresponding years. Since the inventory list for this technology is not available in ecoinvent, the all the environmental flows are obtained from IPPC report [49].

h) De-icing salt manufacturing

De-icing salt is one of the commodities that is available with different chemical bases. The policy of local transportation government is on the optimum use of de-icing salts and, therefore, no policy constraint is included in the salt type [50]. Abundant mass of sodium chloride salt in Quebec can guarantee long-term supply of roads de-icing. The affected technology would be the most preferred technology since the trend of salt manufacturing has been almost steady since 2010 [51]. The highest short-term price between the alternatives of de-icing salt is calcium chloride, which is able to de-ice the road surface at the same efficiency level of sodium chloride. The lowest price belongs to sodium chloride and the affected supplier would be the mine with the shortest distance of transportation.

i) Bitumen

Bitumen, gasoline, and diesel are of the co-products of crude oil refining. Same as other multifunctional processes, determining co-product(s) should be identified to assign the environmental impacts of the process. The determining co-product(s) are the product(s) of a multifunctional process for which a change in demand will affect the production volume of the process.

Since the road network in Quebec is already developed and no further significant capacity expansion is expected, demand for bitumen will only come from roads repair and maintenance as well as reconstruction. As can be observed in Figure A3.5, the demand for this product is slightly decreasing and the same decrease trend is forecasted until 2021 [52]. To identify the most likely supplier that is affected by bitumen demand, the speed of replacement rate for production equipment is considered. Higher decrease rate of the capital replacement than the overall market trend will lead to selecting the most competitive supplier in the market, and vice versa for the long-term affected supplier [53]. In general, the replacement rate for equipment is determined by the inverse estimated lifetime of the equipment. For the refinery, it is stated that the capital equipment lifetime is approximately 20 years [54].

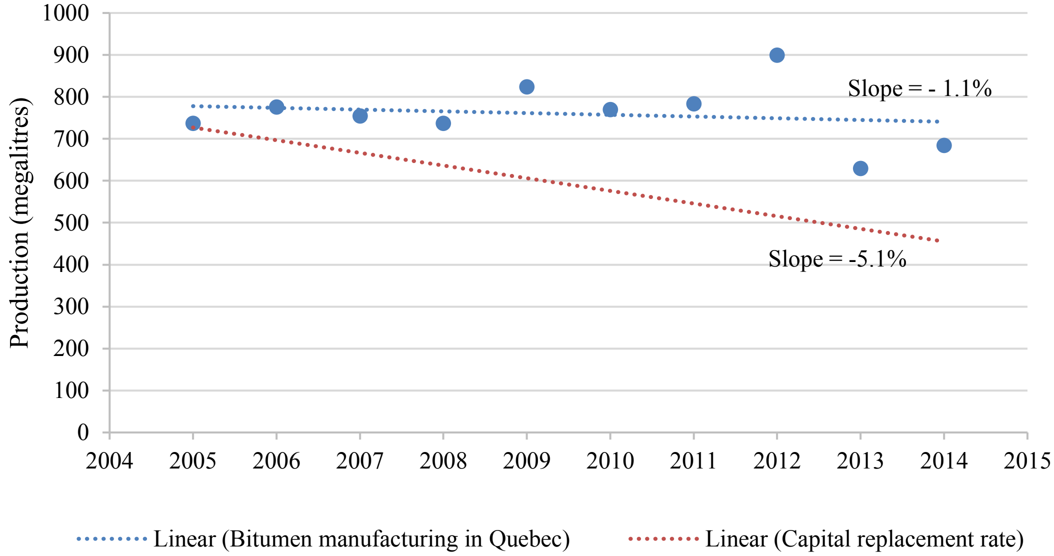

Figure A3.5. Annual bitumen production in Quebec [55] and refinery capital replacement rate [54]

Many factors, such as supply (affected by current condition and future expectation for capacity, geopolitics, weather, etc.), demand (affected by current condition and future expectation for economic and population growth, personal and industrial transport, etc.), physical balancing, and market behaviour (options, swaps, spreads, and futures in energy price) influence the formation of crude oil prices. Supply contracts of oils are short-term, and sources can be changed very quickly if crude oil producers offer better prices [56]. Crude oil is totally imported to Quebec and the supplier countries varied significantly per year [24]. The import data and corresponding price of imported crude oil are not available and, therefore, the crude oil market is simplified by classifying the suppliers to the following three categories.

Current suppliers of crude oil in Quebec are the U.S., Western Canada, and the organization of the petroleum exporting countries (OPEC). For the OPEC crude oil importing to Quebec, the low-sulfur type of crude oil was considered (which comes from Algeria, Nigeria, etc.) [57]. The sources of crude oil in the U.S. have been greatly increasing their market share, because of lower prices offered by the American and Canadian producers, notably for oil coming by train and ship from North Dakota and Texas, respectively. The bitumen production price is adjusted based on the price of the crude oil assuming a similar cost of the refinery for the different alternative suppliers. Therefore, according to Figure A3.6, the WCS oil, which yields almost 29% of bitumen per barrel of crude oil, has a lower price in the market compared to the other suppliers. For the short-term affected technology of bitumen, the U.S. crude oil importing by train was taken into account. For the long-term effect of the increase in bitumen demand, we assume that the oil production in WCS is the affected supplier (see Figure A3.6). It will naturally receive a lower price in the marketplace due to less valuable refinery products but more residual materials such as bitumen.

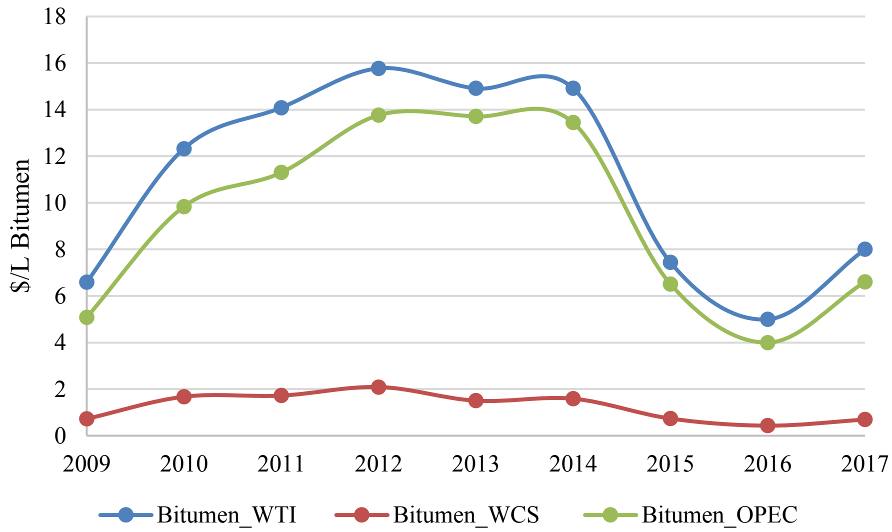

Figure A3.6. The annual price of crude oils normalized for production of 1-liter bitumen from different suppliers of Quebec [58]

Co-products are always dealt with using substitution, which is the preferred approach in ISO 14044. Since bitumen is a co-product of petroleum production, the procedure of identifying the determining product is necessary in order to assess the consequence of increasing the change in the demand of the multifunctional process. This procedure is extensively described in Schmidt and Weidema [59], and Weidema [8]. The refinery is assumed as a joint process (i.e. the output of the co-products cannot be varied independently) and a change in demand for one of the co-products may increase in the production volume of the process.

The outputs of WCS oil are significantly different from those in WTI and OPEC oils since the latter yields fewer residues and more lighter co-products. The petroleum products do not have any alternative way of production although some flexibility exists, notably in the bitumen market (e.g. bioasphalt as a long-term substitution of bitumen). Therefore, a change in the production volume in short-term affects the output, pricing and consequent consumption of all the other refinery co-products. According to Weidema [3], joint products that do not have any relevant alternative production routes have the same normalized market trend, since only then the market will be cleared. In this situation, a change in demand for one of the co-products will influence the production volume of the crude oil in proportion to its share in the gross margin of the refinery process (i.e. similar to economic allocation in attributional LCA). The overview of the co-products and their contribution to revenue, induced production, and consumption as well as the net changes in consumption, which are induced by demanding more of each of by-product, are presented in Table A3.2 and A3.3 (WTI oil). The prices of petroleum co-products were obtained from [60], [61], [29, 62] and [63]. The procedure of finding the determining products in a joint production system that have more than one product without alternative production routes are explicitly described [64]. It should be noted that the changes in the content of the other co-products will affect their consumption and disposal phases. Therefore, in case of no alternative for the co-products (Table A3.3), demanding 1-liter bitumen from the short-term supplier induces 0.73 lit crude oil refining (of which 0.03 lit bitumen, see Figure A3.7) and the rest of the demand, i.e. 0.97-liter bitumen, should be supplied from the reduction in consumption of bitumen by the marginal consumers. As a simplification, in this study, it is assumed that the 0.97-liter bitumen is supplied by the un-demanded production induced by other co-products such as diesel and gasoline (See section j. Diesel and gasoline).

Table A3.2. The procedure of identifying the determining product in petroleum production (WTI crude oil)

Product	**Average Output from a Barrel of Oil [65, 66]**	**Price**	**Revenue**	
		$/Lit	**$/Lit crude oil**	**%**
Bitumen	4%	0.64	2.6	3%
Diesel	27%	0.89	24.9	28%
Gasoline	43%	1.08	50.8	58%
Heavy fuel oil	5%	0.45	2.3	3%
Light fuel oil	3%	0.58	1.7	2%
Liquefied petroleum gas	2%	0.46	0.9	1%
Jet fuel	6%	0.81	4.9	6%
Rest (Relatively small quantities)	6%	-	0.0	0%
Total	-	-	88.0	100%

Table A3.3. Induced production of the demanded co-product (highlighted in yellow) and by-products from crude oil refinery of WTI per Lit demand

Induced production when demanding 1 Lit of by-product	**Bitumen**	**Diesel**	**Gasoline**	**Heavy fuel oil**	**Light fuel oil**	**LPG**	**Jet Fuel**
Bitumen	0.03	0.04	0.05	0.02	0.03	0.02	0.04
Diesel	0.20	0.28	0.34	0.14	0.18	0.15	0.26
Gasoline	0.34	0.48	0.58	0.24	0.31	0.25	0.43
Heavy fuel oil	0.04	0.05	0.06	0.03	0.03	0.03	0.05
Light fuel oil	0.02	0.03	0.04	0.02	0.02	0.02	0.03
Liquified petroleum gas (LPG)	0.01	0.02	0.02	0.01	0.01	0.01	0.02
Jet fuel	0.04	0.06	0.07	0.03	0.04	0.03	0.06
Rest	0.04	0.05	0.06	0.03	0.03	0.03	0.05
Induced determining products	0.73	1.01	1.23	0.51	0.66	0.52	0.92
Total induced production	0.73	1.01	1.23	0.51	0.66	0.52	0.92

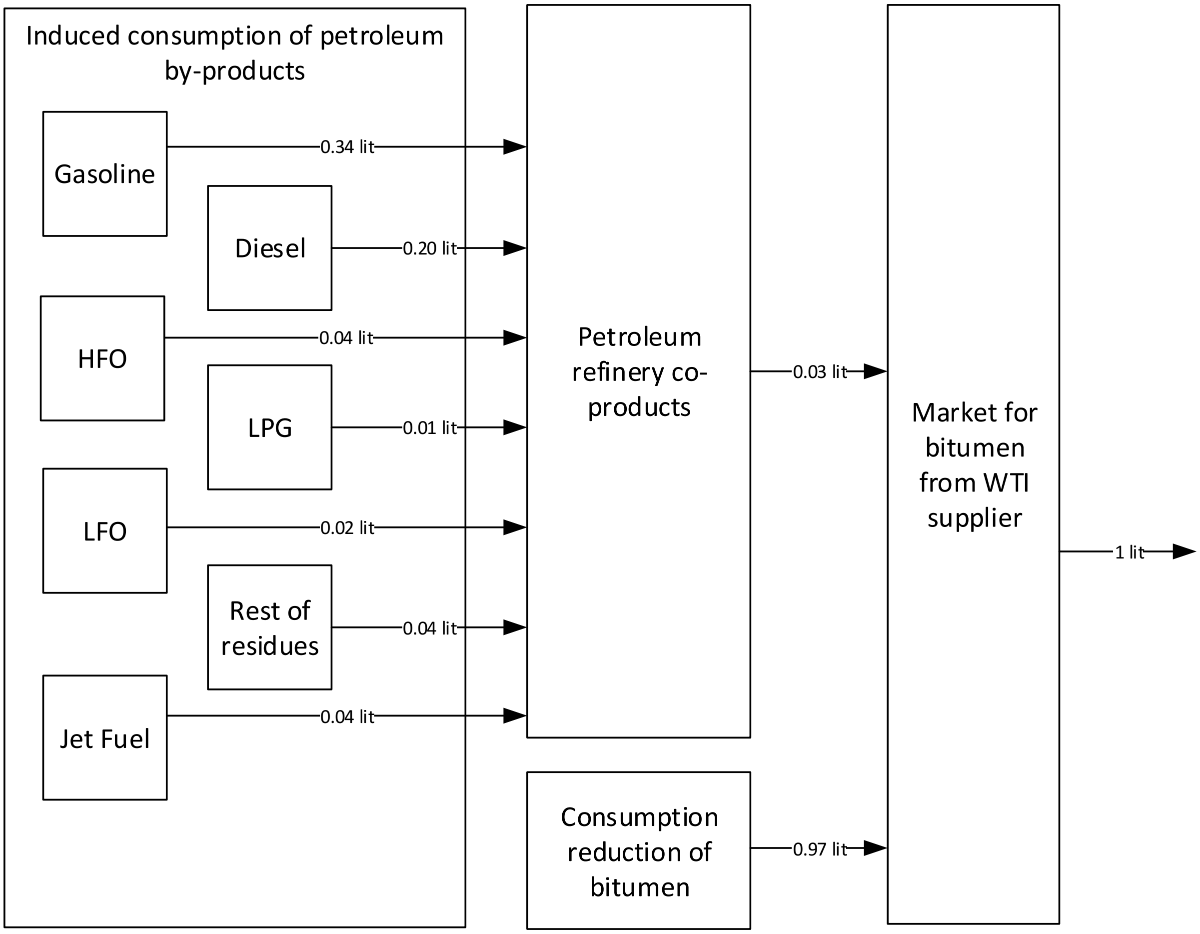

Figure A3.7. Total exchanges in petroleum co-product market due to the short-term change in bitumen demand (LPG= liquefied petroleum gas, HFO= heavy fuel oil, LFO= light fuel oil)

In the long-term scenario, we consider the innovative technology of bioasphalt as an alternative for petroleum bitumen. Therefore, in the first stage, it should be identified if the bitumen is the determining co-product. Since it is assumed that other co-products rather than bitumen have no alternative route of production, the change in the demand of bitumen will not affect the capacity of crude oil refinery production. Instead, the bitumen alternative will supply the change in the demand as the demand for petroleum bitumen is constrained by other co-products. We assumed that the most likely compensating bituminous material as bioasphalt since this is identified as one of the rare products that are able to exert the same properties of petroleum bitumen. The availability of abundant forest wood in Quebec makes the development of bioasphalt very facilitating to change the asphalt-paving industry in the coming years dramatically.

j) Diesel and Gasoline

The short-term and long-term affected technologies for car and trucks fuels were assumed as gasoline and diesel, respectively, mainly because the infrastructure for other technologies such as electric and LPG consuming vehicles are not well developed, and their production is constrained. Nevertheless, the improvement in car fuel efficiency was considered in the modeling and is explained in Section 4 of this appendix. Like the bitumen case, the price of crude oils, which supply the demand in Quebec, is normalized based on the proportion of diesel and gasoline contents in each crude oil supplier. As shown in Figure A3.8 and A3.9, the lowest and highest historical prices of the crude oils normalized for production of gasoline and diesel belong to WTI and WCS suppliers, respectively.

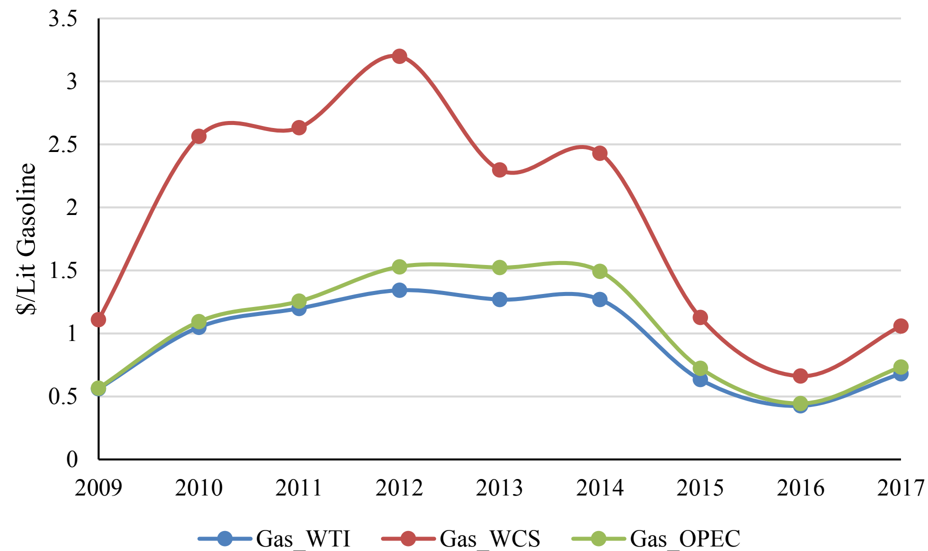

Figure A3.8. The annual price of crude oils normalized for production of 1-liter gasoline from different suppliers of Quebec [58]

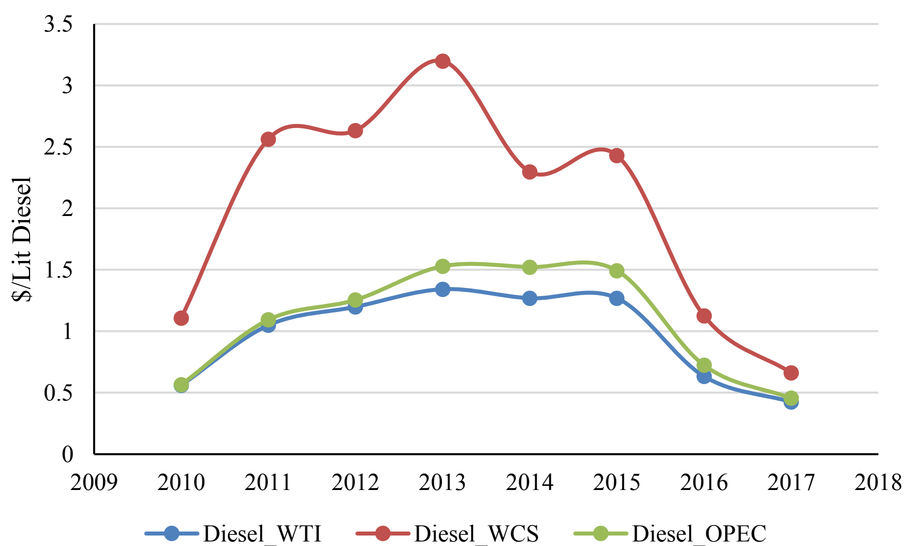

Figure A3.9. The annual price of crude oils normalized for production of 1-liter diesel from different suppliers of Quebec [58]

The outputs of WCS crude oil and their corresponding revenue are presented in Table A3.4. The demand for gasoline and diesel in short-term can induce an increase of 0.23 and 0.13 Lit of the demanded co-products, respectively (The highlighted values in 3rd and 4th columns of Table A3.5). At the same time, the induced production of 0.13 Lit diesel supplies an additional amount of the un-demanded petroleum co-products and therefore inducing an increased consumption of these co-products to clear all the co-products' markets. The induced production of diesel and gasoline in long-term, which are supplied by WTI crude oil, are 0.28 and 0.58 Lit, respectively, as shown in Table A3.4.

Table A3.4. The procedure of identifying the determining product in petroleum production (WCS crude oil)

Product name	Average Output from a Barrel of Oil [67]	Price	Revenue	
		$/L	$/L crude oil	%
Bitumen	26%	0.64	16.6	25
Diesel	10%	0.89	8.9	13
Gasoline	17%	1.08	18.4	27
Heavy fuel oil	18%	0.45	8.1	12
Light fuel oil	15%	0.58	8.7	13
Liquefied petroleum gas	3%	0.46	1.4	2
Jet fuel	6%	0.81	4.9	7
Rest (Relatively small quantities)	5%	-	0.0	0
Total	-	-	67.0	100

Table A3.5. Induced production of the demanded co-product (highlighted in yellow) and by-products from crude oil refinery of WCS per Lit demand

Induced production when demanding 1 Lit of:	Bitumen	Diesel	Gasoline	Heavy fuel oil	Light fuel oil	LPG	Jet Fuel
Bitumen	0.25	0.35	0.35	0.17	0.23	0.18	0.32
Diesel	0.10	0.13	0.13	0.07	0.09	0.07	0.12
Gasoline	0.16	0.23	0.23	0.11	0.15	0.12	0.21
Heavy fuel oil	0.17	0.24	0.24	0.12	0.16	0.12	0.22
Light fuel oil	0.14	0.20	0.20	0.10	0.13	0.10	0.18
Liquified petroleum gas (LPG)	0.03	0.04	0.04	0.02	0.03	0.02	0.04
Jet fuel	0.06	0.08	0.08	0.04	0.05	0.04	0.07
Rest	0.05	0.07	0.07	0.03	0.04	0.03	0.06
Induced determining products	1.0	1.3	1.3	0.7	0.9	0.7	1.2
Total induced production	1.0	1.3	1.3	0.7	0.9	0.7	1.2

The fuel consumption of vehicles induces an extraction of crude oil and at the same time, a significant consumption of other co-products. The short-term affected supplier of gasoline and diesel, i.e. the least competitive one, is identified as the Canadian source. Therefore, the change in demand of one lit gasoline and diesel will induce 1.3 and 1.6 lit Canadian crude oil extraction and refinery, respectively. In addition, the increase in the extraction and the refinery of crude oil induces an increased consumption of the other co-product, such as kerosene, bitumen, fuel oils, and light petroleum gas, since all markets must be cleared. In the long-term, the affected supplier is the U.S. source, as the U.S. crude oil yields larger proportions of valuable refinery co-products, such as gasoline, than those for other suppliers. The induced production rate is estimated as 1.01, and 1.23 lit crude oil for 1-lit change in the demand of gasoline and diesel, respectively.

k) Asphalt production

Asphalt production is following the same trend of the bitumen supply in Quebec as well as Canada. A -0.5% decline in the asphalt production is reported according to the statistics in recent five years. This decline is expected to be continued at the rate of -0.3% in next five years [68]. The lifetime of asphalt plants is used to find the capital replacement rate for the asphalt production. Different lifetimes of asphalt plant are mentioned in the literature (15-35 years [69-71]). Given all the range of possibilities in the plant lifetime, asphalt market trend is still lower than the capital replacement rate (See Figure A3.10). Therefore, the most competitive supplier must be selected as the affected one in asphalt production in long-term. The nearest plant and the lowest long-term cost fuel for different levels of mixture manufacturing will be selected, while the farthest transportation distance was considered for the asphalt affected supplier in short-term.

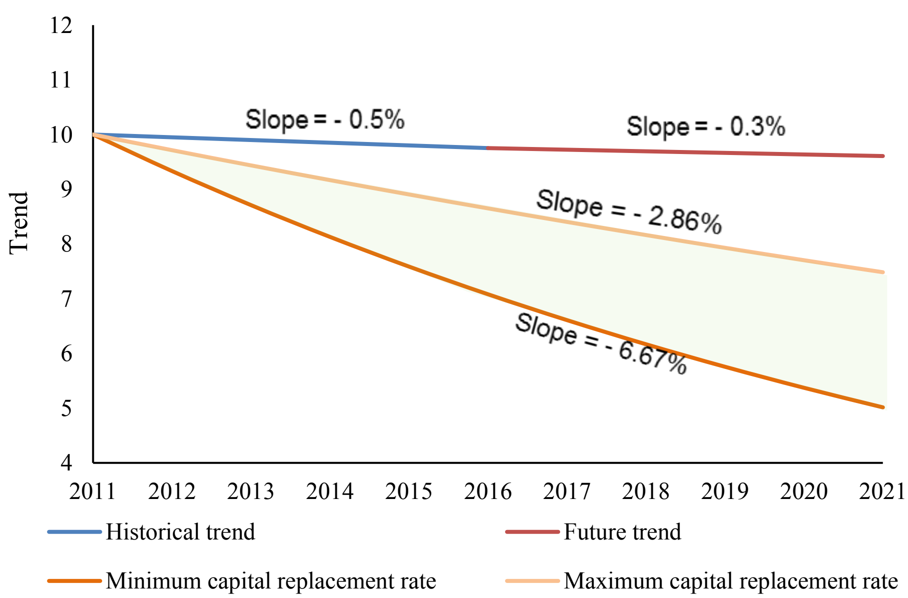

Figure A3.10. Market trend of asphalt manufacturing and possible replacement rate of capital equipment

l) Fuel for asphalt production

Generally, fuels are utilized in asphalt plants are divided into different types of gas fuels (natural gas, propane, and biogas) and fuel oils (heavy and light fuel oils and used oils) [72]. By-product fuels such as biogas and used oils have a negligible contribution to the market, and their production is technologically constrained because the production volume is determined by the demand for main products. Since these by-product fuels are fully utilized in the market, their increased use in the life cycle of pavements results in a corresponding increase in the production of other products that fulfill the same function. According to Figure A3.11 and considering the decrease in heavy fuel oil supply in the region, the light fuel oil is currently the least competitive technology for heat generation in asphalt plants. However, after 2020 it is the natural gas that poses the lowest price for heating. In addition, as stated in cement fuels section, there will be a political constraint on the use of heavy fuel oils in Canada [20]. Therefore, in the short-term scenario, we consider heavy fuel oil as the asphalt-heating supplier (e.g. in pavement construction) and for the prospective scenario, natural gas will be selected (e.g. for the pavement resurfacing as a part of maintenance and repair).

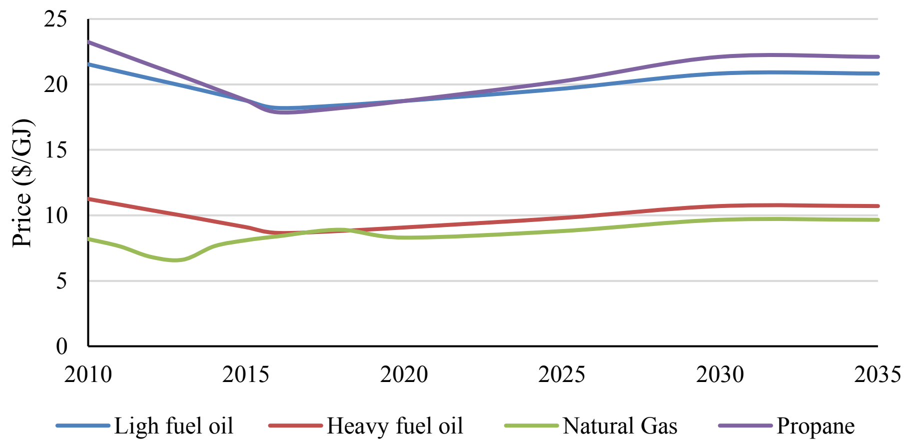

Figure A3.11. Historical and forecast cost of different fuels for asphalt heating [26, 29, 30, 52] (Note: the currency is expressed in $Cdn and are in the base year 2015. Conversion between Canadian and US$, where required, has been done at the rate of $1US = $1.32Cdn.)

m) Electricity production

The affected technologies in short and long-term for electricity generation were already identified in [73]. The wind and gas power plants were considered as the long and short-term technologies.

n) End of life

For the end-of-life scenario, we considered 98% reclamation of asphalt pavements and therefore, avoided burdens of virgin materials and asphalt production, as well as transportation of materials from project to plant, is assigned according to local practices [74]. Replacing virgin coarse aggregate by 90% of concrete mass and recycling of all the reinforcing rebars are the end-of-life scenario of the concrete pavement. Rest of the materials in both alternatives were sent to landfilling site.

Summary of all the affected technologies described in the previous section is presented in Table A3.6.

Table A3.6. Summary of affected technologies in different time horizons

Intermediate flow	Market trend	Short-term affected supplier	Long-term affected supplier	Note
Concrete at batching plant	↗	Farthest ready mixed plant	Nearest ready mixed plant	No technological development due to the lower contributed cost of the batching plant in the purchase price of concrete.
Cement	↗	Farthest cement plant with the oldest technology (dry kiln) in the market	New plant constructed in Port-Daniel (pre-calciner and pre-heater)	The other existing plants are not able to increase their production due to the technological and political constraint.
Sand and gravel	↗	Farthest manufactures sand and gravel mine	Nearest manufactured sand and gravel	The natural sands are not abundant and will be finished in near future.
Water	↗	Water extracted from a well in batching plant	Water extracted from a well in batching plant	-
Chemical admixtures	↗	Oldest technology in chemical admixtures (Lignosulfonate-based)	Latest technology in chemical admixtures (Polycarboxylate-based)	-
Reinforcing rebars	↗	The rebars produced by German manufacturers with blast oxygen furnace technology	Rebars produced by Canadian manufacturers with blast furnace with carbon capture and storage and top gas recycling technology	-
De-icing salt	↗	Calcium chloride	Sodium chloride	Abundant (no resource constraint) and the lowest cost
Car Fuel	↗	WCS crude oil	WTI Crude Oil	-
Bitumen	↘	WTI Crude oil	Bio asphalt	In short-term, no alternative way to produce all the petroleum co-products. In long-term, only bitumen has alternative production route.
Fuels for asphalt production	↘	Light fuel oil	Natural gas	-
Fuels for clinker production	↗	Natural gas	Forest biomass near the plant (St-Elzéar)	-
Electricity	↗	Gas power plant (import)	Wind farm	-

3. Dynamic modeling of use phase

In this section, the procedure of use stage modeling for each investigated as well as the details of input parameters are presented.

3.1. Car fuel consumption

The interaction between pavement and diverse types of vehicles can cause an increase in fuel consumption due to energy dissipation or rolling resistance, is affected by the specifications of the vehicle, such as weight and power, and tire properties, such as thickness and composite type, As well as the characteristics of the pavement properties, such as flexibility and surface roughness.

a) Car fuel efficiency and the rebound effect

The changes in the pavement specifications, such as surface roughness and rigidity, can modify the quantity of the fuels. This change in fuel consumption (lit/km) is called "Pavement-induced fuel efficiency" in this study. We considered the contribution of the pavement system, and specifically, the surface properties (IRI) and the structural effects (rigidity) of the pavement, which are explicitly presented in section 4.1.2 and 4.1.3. Another parameter that adjusts the time-dependent fuel consumption of vehicles is "technologically-induced fuel efficiency". Fuel-efficient vehicles use less gasoline or diesel per traveled kilometer, which results in saving on fuel cost. The enhancement in the average car and trucks fuel consumptions were obtained from historical data [75] and were deployed in the net change of time-dependent fuels consumption both for surface roughness and rigidity-induced changes. In this study, although simplified as a linear regression, Eq. (1) and (2) were used for estimating the evolution of technical efficiency for gasoline and diesel vehicles, respectively.

$$\left(\frac{\partial E(t)}{E(t)}\right)gas = 0.9085t \qquad \text{Eq. (1)}$$

$$\left(\frac{\partial E(t)}{E(t)}\right)diesel = 0.9606t \qquad \text{Eq. (2)}$$

Where $\frac{\partial E(t)}{E(t)}$ represents the relative change in fuel efficiency, which is applied to the fuel economy of vehicles in the technology matrix. The changes in vehicles fuel consumptions, and specifically, the improvement in car fuel efficiencies, can be affected by a rebound effect, which is a tendency for road users to travel for longer distances or to switch to larger vehicles and as a result, counteracting a certain part of the fuel efficiencies. The total rebound effect of the improvement in fuel efficiency on gasoline consumption can be divided into the price and the income effects. The price effect refers to purchasing an excessive quantity of gasoline by consumers due to the decrease in fuel cost. The income effect implies that road users have more income to spend on gasoline and other goods. In this study, we included the direct rebound effect of changes in fuel efficiency, which refers to changes in gasoline consumption through both price and income effects.

A rebound effect implies that the excessive consumption will offset the increase in efficiency. The magnitude of the rebound effect is thus critical for the proper design of policies for evaluating the effectiveness of both pavement-induced and technologically-induced fuel efficiency. Rebound effect from fuel efficiency is defined as a relative change in gasoline consumption following a change in behavior due to a relative change in fuel efficiency, or the elasticity of gasoline consumption with respect to fuel efficiency as shown in the Eq. (3).

$$\eta_{\varepsilon} = \frac{\partial \mathrm{FE}/_{\mathrm{FE}}}{\partial \varepsilon/_{\varepsilon}} \qquad \text{Eq. (3)}$$

Where, FE and ε represent fuel consumption (in this case, gasoline) and fuel efficiency, respectively. The difference between the actual response of gasoline demand to an increase in efficiency and a full response, where efficiency elasticity is equal to 1, is the rebound effect of fuel efficiency. Therefore, the lower the efficiency elasticity, the higher the rebound effect. The procedure of estimating the rebounding effects and their corresponding values for Quebec households were adopted from [76]. The modified fuel efficiency of cars is therefore calculated by multiplying the rebound effect with the fuel efficiencies induced by technology and pavement characteristics.
The demand elasticities and the implied rebound effects are significant in the long-term as the fuel is considered as a basic need. Therefore, the rebound effect was considered in the modification of the fuel efficiencies in long-term. The function of time-dependent rebound effect is described as a discrete function according to Eq. (4):

$$R(t) = \begin{cases} 0 & \mathrm{T}_{\mathrm{Shift}} \leq t \\ \eta_{\varepsilon} & \mathrm{T}_{\mathrm{Shift}} > t \end{cases} \qquad \text{Eq. (4)}$$

Where $\mathrm{T}_{\mathrm{Shift}}$ is defined as the time after the beginning of life cycle when the change in demand will affect a new capacity installation.

One should note that the rebound effect can vary from one income-level consumer to another. For example, low-income households spend more on energy relative to their income rather than high-income households. On the other hand, high-income consumers are likely to afford to switch to larger cars as fuel cost decreases. Therefore, the variability of the consumer income-level was considered in this study.

b) Car fuel consumption due to surface roughness

The roughness of pavement is generally measured by International Roughness Index (IRI) corresponding to unevenness of pavement surface (0.5-50 m). Figure A3.12 shows the procedure of estimating the time-dependent values of IRI.

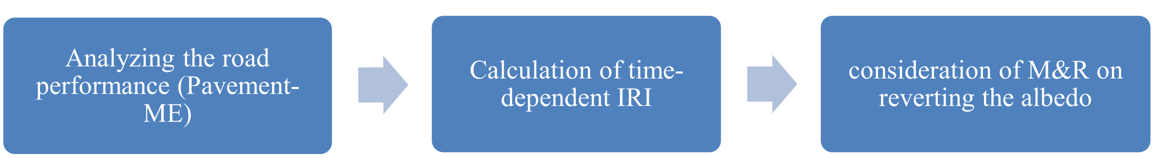

Figure A3.12. Estimation of time-dependent IRI for each scenario using Pavement-ME software

After the calculation of IRI for each scenario, the surface roughness-induced fuel consumptions were calculated and were linked to the affected technology, as shown in Figure A3.13.

Figure A3.13. The procedure of calculating inventory data for surface roughness-induced fuel consumption

The details of modeling and the explanation of time-dependent parameters are presented in this section. The extra distance traveled by the vehicles needs to be calculated in the first step. It should be noted that the method presented assumes that the change in IRI varies for all ADT since the IRI(t) is measured from the outer lane, which has the highest damage due to the significant traffic of trucks load. According to Eq. (5), the change in traveled kilometer for vehicle type i in lane j at time t is estimated as:

$$\Delta \mathrm{VKM_i}\ (t) = \sum_{j=1}^{n}\left(\mathrm{ADT}_i^j . \mathrm{F}_{v_i} . l . (1+R)^t . \left[\mathrm{IRI}_{BAU}^j(t) - \mathrm{IRI}_{ALT}^j(t)\right]\right) \quad \text{Eq. (5)}$$

Where, ΔVKM is the extra km that vehicle type i, ADT is the traffic volume, F_v is the percentage change in fuel consumption per unit change in IRI, R is the percentage of traffic growth, and IRI_{BAU} and IRI_{ALT} are the international roughness index (in m/km) of BAU and ALT cases, respectively.

The change in fuel consumption (Lit) at time t for each vehicle type i is then calculated as:

$$\Delta f_{IRI}(t) = \frac{\Delta \mathrm{VKM_i}\ (t)}{\mathrm{FE_i}\ (t)} \qquad \text{Eq. (6)}$$

In Eq. (6), ΔF_{IRI} and FE_i represent the change in fuel consumption (Lit) and fuel economy (km/Lit) for vehicle type i, respectively. Then, the changes in fuels consumption for each type of vehicle i at time t was linked to the short-term or long-term affected technologies according to the time occurrence.

The IRI progression as a function of the pavement use must be predicted for the life cycle of the project. To have a more accurate estimation of the IRI, the pavement design software, Pavement-ME, was employed. This software calculates the IRI progress specified by the Mechanistic-Empirical Pavement Design Guide (MEPDG) considering different specifications such as traffic load, environment condition (temperature and humidity), and materials used in the pavement layers.

Diamond grinding is a usual repair for concrete pavements and specifically, reducing the unevenness of the textured surface. To estimate the IRI change after grinding, Eq. (7) based on data from Caltrans grinding project was employed [77]. This equation consists of a linear regression model, where IRI after grinding (IRI_{Drop}) is related to IRI before grinding ($IRI_{before\ Grinding}$).

$$\mathrm{IRI_{Drop}} = -0.6839 + 0.6197\mathrm{IRI_{before\ Grinding}} \qquad \text{Eq. (7)}$$

For asphalt overlay work, the achieved driving quality is influenced by the roughness of the existing surface, the thickness and number of layers, and the extent of shape correction undertaken by regulation or cold planning. As shown below, Eq. (8) provides a guide to the IRI achievable with a single layer of asphalt [78]:

$$\mathrm{IRI_a} = 0.3 + (0.667\ \mathrm{IRI_b}) - (0.0109\ \mathrm{T}) \qquad \text{Eq. (8)}$$

Where, IRI_a and IRI_b are the roughness after and before the asphalt overlay (m/km), respectively and T represents the total thickness of overlay (mm).

c) Car fuel consumption due to surface rigidity

The dissipated energy as a consequent of pavement rolling resistance must be compensated by extra engine power. The model of deflection-induced pavement-vehicle interaction developed by Akbarian [79, 80] and Louhghalam et al. [81, 82] was an excel-based tool named GEN II, which was employed to calculate the dissipation of energy in pavement material and vehicle suspension system (Figure A3.14). The deflection-induced truck fuel consumption was shown as a significant source of emission in the use phase of pavements, whereas the contribution of deflection-induced car fuel consumption to the total emissions was insignificant [83]. One of the important parameters used to estimate deflection-induced fuel consumption is the ambient temperature. It was already shown that the excessive fuel consumption related to the rigidity of pavements has no difference in 0°C while this difference in 30°C is more than 250% [84]. Therefore, we considered the monthly fuel consumption to improve the accuracy of the model estimation. Nevertheless, the effect of the monthly temperature variability was considered in the uncertainty analysis to evaluate the robustness of the conclusion.

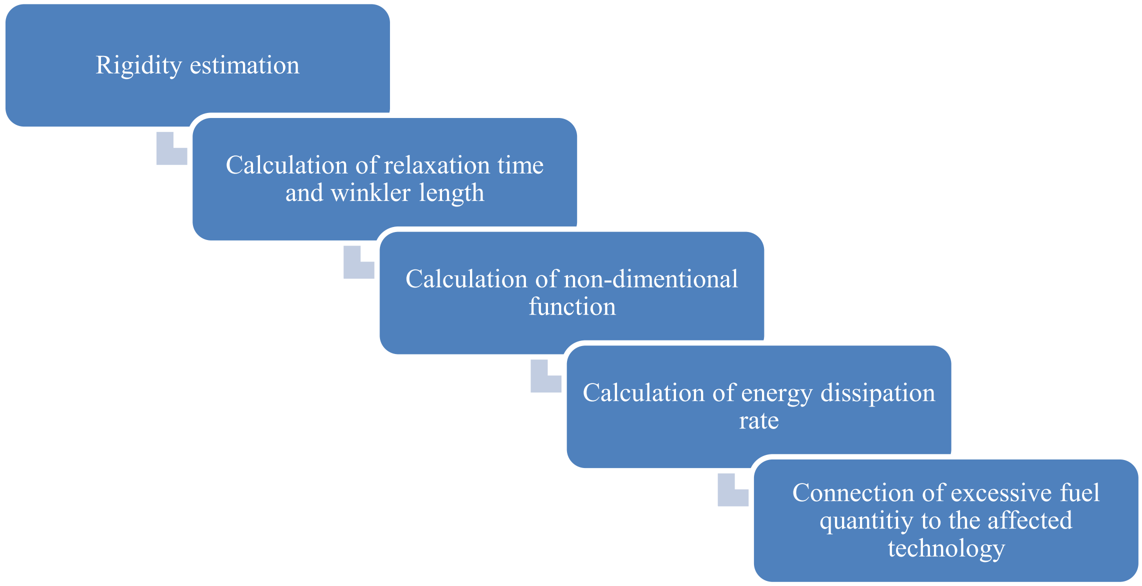

Figure A3.14. The procedure of calculating inventory data for flexibility-induced fuel consumption

3.2. Albedo effect

Albedo is a scale that shows what fraction of solar shortwave radiation is reflected when it reaches a surface. If the solar radiation is fully absorbed by the surface, then a value of 0 will be attributed to the surface and if the solar radiation is fully reflected, then the albedo of the surface is equal to 1. The albedo of pavement surface can affect the ecosphere in two ways: directly through adjusting the radiative forcing and indirectly by changing the ambient temperature. In this study, the direct and the indirect effects of albedo are called RF and UHI, respectively and the procedure of modeling is explained in section 4.2.1 and 4.2.2. The procedure of calculating time-dependent albedo is shown in Figure A3.15. The dynamic values of the albedo were estimated based on the mix designs and according to the equations proposed by Levinson and Akbari [87], and Richard et. al [88].

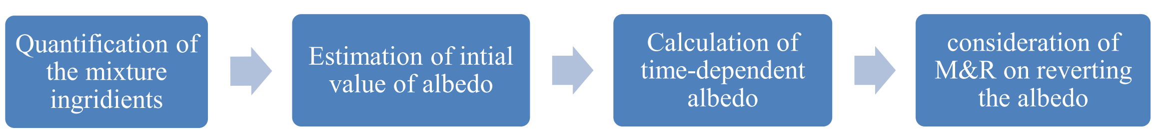

Figure A3.15. Estimation of time-dependent albedo for each scenario using Pavement-ME software

a) Modeling RF effect of albedo

In the direct effect of albedo, the changes to the pavement surface can deploy a radiative forcing by unbalancing the total shortwave radiation reflecting the space. Therefore, the radiative balance at the top-of-atmosphere (TOA) will change due to this perturbation. RF is defined as quantitative comparisons of the strength of different human interventions and natural means in causing climate change [89]. In fact, once the RF is exerted, the climate tends to balance itself to recover equilibrium by means of changes in temperature. Akbari et al. [90] estimated a

reduction of 2.55 kg CO_2 per 0.01 increase in surface albedo for one square meter. It should be noted that adopting a constant value of CO_2 reduction per albedo change may not pose the real variation within different geographical contexts and along different months of a year, where shortwave radiation varies. Hence, we look for a time-dependent modeling framework for the RF effect to take in to account the temporal and regional aspects of the case study.
The procedure of calculating the RF effect is summarized in Figure A3.16. The first step is to calculate the net RF per a standard albedo change to estimate the change in RF-induced by changing the surface reflectivity. According to Muñoz et al. [91], the effective RF as a result of a change in a surface albedo can be calculated as:

$$\Delta \mathrm{RF}_{\mathrm{alb}}(\mathrm{t}) = -\mathrm{R_s}.\mathrm{T_a}.\Delta\alpha_{\mathrm{s}}(\mathrm{t}).\frac{Area_{FU}}{Area_{Earth}} \qquad \text{Eq. (9)}$$

Where RF_{TOA} is the downward solar radiation at TOA; R_s is the downward solar radiation at the surface of the Earth; T_a is an atmospheric transmittance factor expressing the fraction of the radiation reflected from the surface that reaches the TOA; $\Delta\alpha_s$ is the change in the surface albedo; and localization factor is the pavement functional area ($Area_{FU}$) divided by the surface area of the earth ($Area_{earth}$). The daily average R_s of the latitude and longitude of Montreal city was obtained from a 10-year daily average surface insolation recorded and obtained by NASA database and a global average T_a of 0.854 is used in this calculation. The monthly averaged values were calculated from the daily RF and the estimated forcing due to the time-dependent change in the reflectivity of pavements was computed by multiplying the difference in the surfaces albedo by the monthly forcing values.

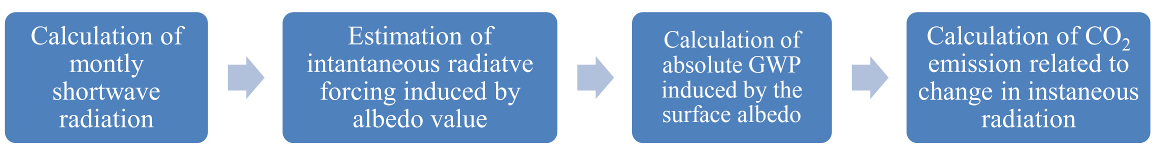

Figure A3.16. The procedure of calculating inventory data for RF effect and linking to CO_2 balance

The next step is to calculate the absolute global warming potential (AGWP) induced by this RF change. By dividing the AGWP of RF change to AGWP of CO_2, the ΔGWP of RF can be calculated as:

$$\Delta GWP_{alb} = \frac{\int_0^{TH} \Delta RF_{alb} dt}{\int_0^{TH} RF_{CO_2} dt} \qquad \text{Eq. (10)}$$

The installation of a reflective pavement induces a one-time step change in the radiation balance of the earth. To simplify the integration in Eq. (10), we assumed that the radiative effect per unit of change in albedo remains constant for the whole service life (Figure A3.17) of the pavement but the value of albedo assigned to the RF will change as a function of time.

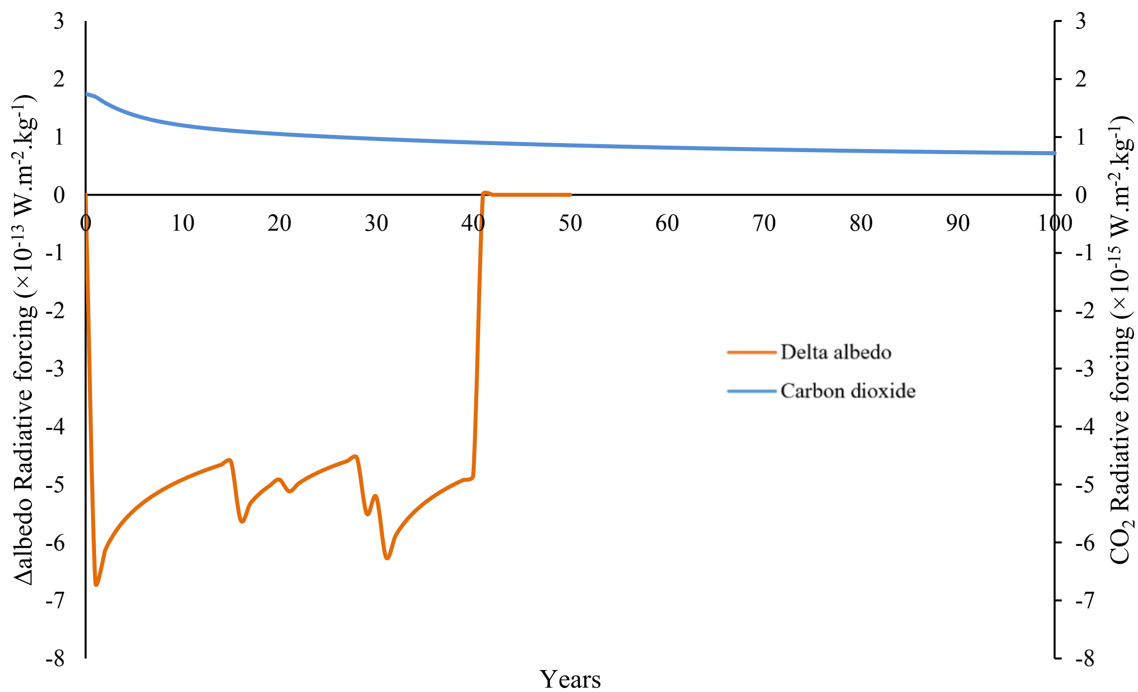

Figure A3.17. Schematic view of time-dependent instantaneous radiative forcing of a unit mass pulse emission at time zero for carbon dioxide and radiative forcing induced by albedo change

For the static CLCA, we considered the 9.26E-15 W.yr/m^2/kgCO_2 as the value of denominator in Eq. (9). On the other hand, for the dynamic LCA, the dynamic inventory for RF_{alb} is obtained by dividing the life cycle into one-year time steps and by adding the emissions induced by albedo change occurring at every time step. Inspiring from the study conducted by Levasseur at al. [92], the following equation was computed to calculate the cumulative GHG emissions induced by ΔRF_{alb} at time t:

$$\Delta GWI_{alb}(t) = \sum_{j=0}^{t}\left(\frac{\int_{j-1}^{j} \Delta RF_{alb}\, dt}{\int_{t-j-1}^{t-j} RF_{CO_2}\, dt}\right) \qquad \text{Eq. (11)}$$

Eq. (11) implies that to compute the change in the impact of global warming at a given time t, herein illustrated as ΔGWI_{alb} (t), caused by a given albedo change, the induced RF occurring at time t should be divided by the RF_{CO2} at time 0. We then add the score assigned to the total RF occurring at year t-1 divided by the RF_{CO2} at time 1 (because it has been released one step back) and so on, until we finally add the total albedo-induced RF occurring at time 0, divided by the RF_{CO2} at time t.

b) Modeling UHI effect of albedo

Changes to the surface albedo of pavements in the urban area contribute to a phenomenon known as Urban heat island (UHI) effect. The term UHI implies the warmth of the earth surfaces and the surrounding atmosphere in urban areas compared to the nearby rural areas that have not been urbanized yet. Elevated temperature during summertime leads to an increase in cooling energy demand for occupied buildings that are equipped with cooling systems. As a consequent of the increase in electricity consumption, there are some indirect emissions related to the surface reflectivity (in contrast with the direct relation of surface reflectivity to RF effect). One should note that the impacts of increased pavement temperatures on UHI are not always negative. The positive impacts of the UHI effect are well-reflected in higher altitude regions that receive less insolation and sun rays is perpendicular throughout the year. The UHI effect can pose a negative impact during hot seasons and in winter, it can also bring benefit to the occupants of the spaces near pavement surfaces by increasing the temperature and less heating energy consumption [93]. Therefore, both sides of the UHI impacts should be considered when evaluating the effect of pavements albedo, especially in near-surface effect, which is influencing to human comfort. To achieve this goal, we developed a model for assessing the environmental consequences of UHI effect stemmed from the pavement albedo change. The methodology of this model is summarized in Figure A3.18. It should be noted that in this method it is assumed that other conditions are constant and the change in pavement surface albedo is dominant in changing the temperatures. However, it might not be the case in a region that has many snowing days. In this condition, the albedo might be much higher in winter due to the high reflectivity of snow covering low-reflectivity surfaces, which might reduce its contribution to UHI by causing fewer surfaces to absorb radiation from the sun [94].

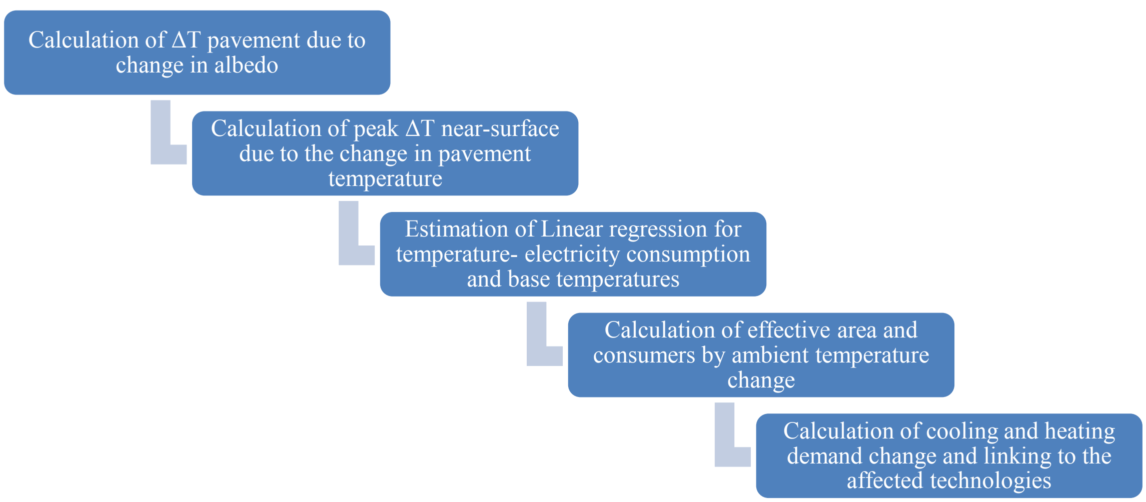

Figure A3.18. The procedure of calculating the change in electricity demand due to UHI effect

We calculated the change in the temperature surface of pavement as a function of albedo change using the empirical relationship between the temperature adjusting by albedo change and global peak solar radiation intensity as [95]:

$$\Delta T_{alb} = 6000q \qquad \text{Eq. (12)}$$

Where q is peak global solar radiation coming to the pavement surface (W/m^2); ΔT_{alb} is the change in pavement surface temperature due to 0.1 change in pavement surface albedo (°C/0.1

albedo). As shown in Eq. (12), the global solar radiation plays an important role in the pavement temperature change. Similar to the RF effect, we used the average 10-year monthly date to obtain the global solar radiation for Montreal city [96].

The next step in calculating the UHI effect is linking the induced change to ambient temperature to the change in pavement surface temperature. To do so, Therefore, we considered the model developed by Li [93] to estimate the temperature change as:

$$T_z = (T_s - T^+).\, e^{(-5.13-0.57WS)\frac{Z}{Z^+}} + T^+ \qquad \text{Eq. (13)}$$

Where T_z is the near-surface air temperature at height Z (in °C); T_s is the surface temperature (in °C); Z^+ is the upper bound of height considered in the model (in m) assuming $Z^+=1$ m; T^+ is the near-surface air temperature at Z^+ (in °C); Z is the height above the pavement surface (in m); and WS is wind speed at 2m height (m/s). Therefore, according to Eq. (14), the change in near-surface temperature can be computed as:

$$\Delta T_z = \Delta T_s.\, e^{(-5.13-0.57WS)\frac{Z}{1}} \qquad \text{Eq. (14)}$$

Where ΔT_z and ΔT_s are the changes in ambient temperature and surface temperature, respectively. The limitation of using this model for the UHI effect is that the spatial variation of near-surface air temperature is in the range of up to 1 m from the surface. Therefore, we assumed the temperature change profile at this height and extend this temperature change for the whole urban area.

To simulate a building energy, we used the DOE-2.1 software and considered the last 10-year hourly temperature in the region. A typical residential building was modeled considering the electricity consumption change as a function of air temperature in summer and winter. The base heating and cooling temperatures during awake and asleep times were considered. The variability of these temperatures was also taken into account in the uncertainty analysis. The electricity consumption values as a function of air temperature are shown in Figure A3.19.

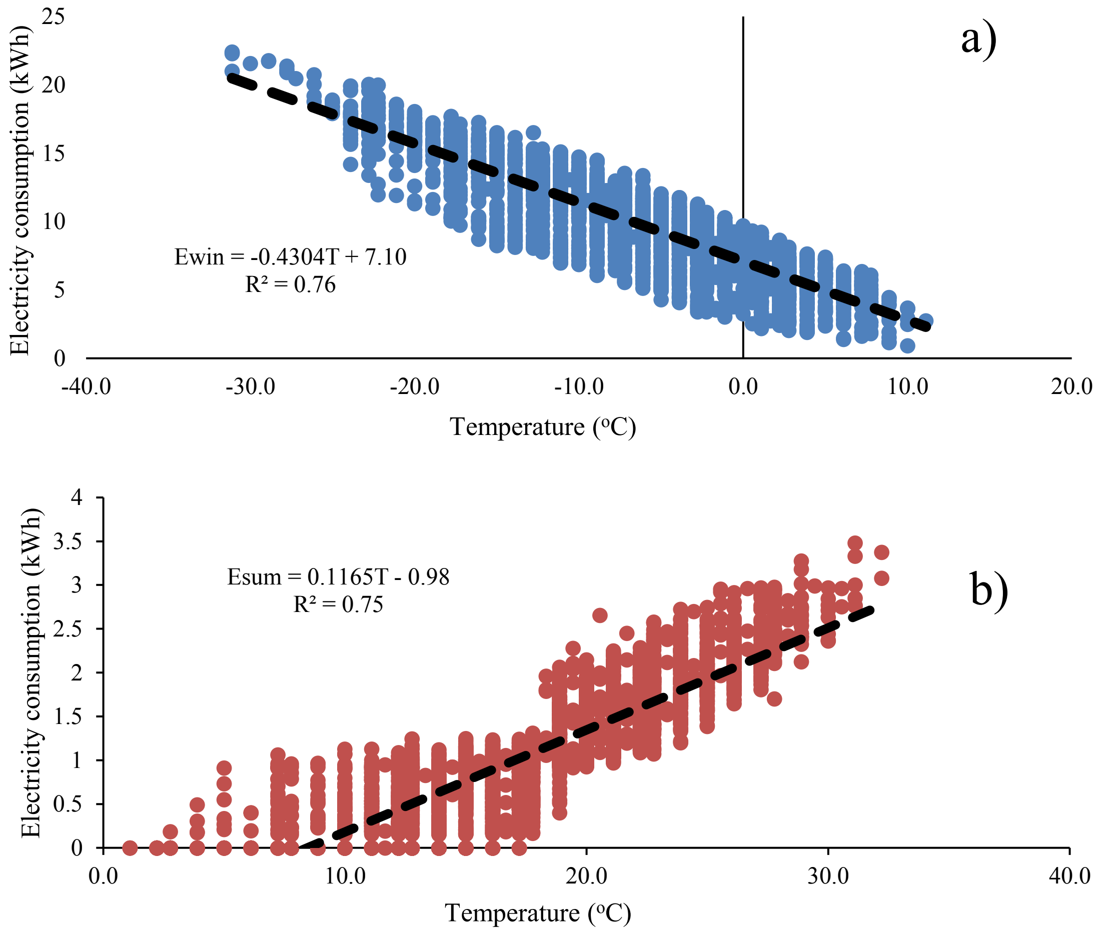

Figure A3.19. Analysis results of electricity consumption as a function of hourly temperature for winter a) and summer b)

In the last step, we used the following equation to calculate the monthly change in electricity consumption for the summer season of the urban areas considering the effective consumers and areas in the city:

$$\Delta f_{elec(sum)}(t) = \begin{cases} \frac{dE}{dT_{sum}}.\Delta T_z(t).U_h.U_p.U_{AC}.A_p \quad \text{for} \quad T_m \geq T_{sum} \\ 0 \quad \text{for} \quad T_m < T_{sum} \end{cases} \qquad \text{Eq. (15)}$$

And for the winter:

$$\Delta f_{elec(win)}(t) = \begin{cases} \frac{dE}{dT_{win}}.\Delta T_z(t).U_h.U_p.U_{AC}.A_p \quad \text{for} \quad T_m \leq T_{win} \\ 0 \quad \text{for} \quad T_m > T_{win} \end{cases} \qquad \text{Eq. (16)}$$

Where $\Delta f_{elec(sum)}$ and $\Delta f_{elec(win)}$ are the change in electricity demand in summer and winter, respectively (in kWh); ΔT_z is the change in air temperature (in °C); U_h is the percentage of household in urban area; U_p is the total number of households; U_{AC} is the percentage of household in urban area that uses air conditioner in summer and winter, A_p is the percentage of the urban area surface covered by the pavement functional unit, T_m is monthly temperature in summer and winter; and T_{sum} and T_{win} are the base temperatures in summer and winter, respectively. As a simplification of this model, we assumed that the buildings are uniformly distributed throughout the city of Montreal using similar cooling and heating equipment. However, the number of stories and type of the HVAC system can be changed from one building to another. More investigation on the effect of real urban texture with consideration of various HVAC systems is required through global system analyzing systems, such as geographic information system (GIS).

3.3. Carbonation

Methodology for implementation of carbon uptake of concrete pavement during its life cycle will be proceeded in three steps according to Figure A3.20:

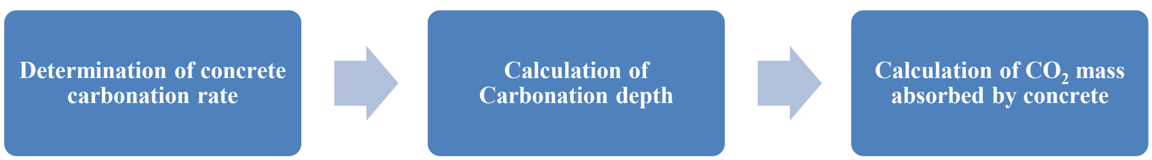

Figure A3.20. The procedure of calculating inventory data for carbonation effect and linking to CO_2 balance

The values summarized in Table A3.7 are used to determine the concrete carbonation rate obtained from Lagerblaad [97].

Table A3.7. The proposed value of concrete carbonation rate ($mm/\sqrt{year}$) [97]

Compressive Strength	< 15 MPa	15-20 MPa	25-30 MPa	> 35 MPa
Wet/Submerged	2	1	0.75	0.5
Buried	3	1.5	1	0.75
Exposed	5	2.5	1.5	1
Sheltered	10	6	4	2.5
Indoors	15	9	6	3.5

In the second step, the carbonation depth was calculated based on Eq. (17) which is popular as Fick's 1st law:

$$D_c = k\sqrt{t} \qquad \text{Eq. (17)}$$

Where D_c is the carbonated depth (mm); k is carbonation rate ($\mathrm{mm}/\sqrt{\mathrm{year}}$).
The depth of carbonation refers to the depth at which the calcium in the concrete can potentially bind to the atmospheric CO_2. However, not all of the calcium in the concrete is expected to bind to CO_2 molecules; the binding efficiency is suggested to be roughly 75% [98]. The mass of CO_2 that is absorbed in time t, $\Delta GWI_{carb}(t)$, is given by Eq. (18):

$$\Delta \mathrm{GWI}_{\mathrm{carb}}(\mathrm{t}) = \mathrm{D_C}(t).\mathrm{c.CaO.r.A.M} \qquad \text{Eq. (18)}$$

Where D_c is the carbonation depth; t is service life (year); c is the quantity of Portland cement (kg/m^3 concrete); CaO is the amount of CaO in Portland cement (%); r is the proportion of calcium oxide that can be carbonated (75%); A is the exposed surface area of concrete (m^2/kg); and M is the chemical molar fraction of CO_2/CaO.

3.4. Lighting

Based on the ability to reflect visible light, roads are grouped into 4 classifications: R1 to R4 [99]. Given the pavement material and the functional classification of the roadway (arterial, freeway, collector, etc.), AASHTO and other authorities have produced recommendations for lighting requirements [100, 101]. The procedure of change in the demand values of electricity is summarized in Figure A3.21.

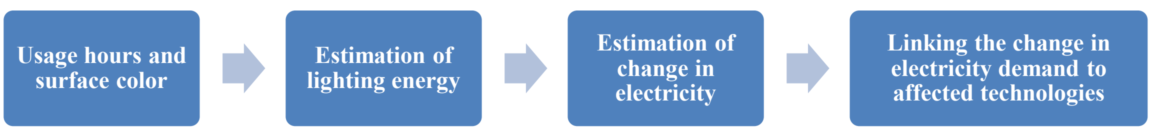

Figure A3.21. The procedure of calculating inventory data for lighting electricity and linking to affected technologies.

Table A3.8 shows a description of the classifications and a sample of illumination demand for arterial and freeway facilities. Frequently, concrete pavements are classified as R1 while asphalt pavements are classified as either R2 or R3.

Table A3.8. Overview of pavement class descriptions and illumination demands Class

Road Class	Description	Illumination Demand (lux)	
		Arterial [96]	Freeway [97]
R1	- Portland cement concrete road surface - Asphalt road surface with a minimum of 15% of the aggregate composed of artificial brightener aggregates	12	6
R2	- Asphalt road surface with an aggregate composed of a minimum 60% gravel (diameter > 10mm) - Asphalt road surface with 10-60% artificial brightener in aggregate mix	17	9
R3	- Asphalt road surface with dark aggregates - Asphalt road surface with rough texture after some months of use	17	9
R4	- Asphalt road surface with very smooth texture	15	8

As the illumination demand is specified, the electricity need for supporting lighting will be calculated based on Eq. (19):

$$\Delta \mathrm{f}_{\mathrm{elec(light)}}(\mathrm{t}) = \mathrm{E}_{lum}.\mathrm{hr.light}.A_{FU} \qquad \text{Eq. (19)}$$

Where $\Delta f_{elec(light)}$ is electricity demand change for road illumination (kWh); E_{lum} is electricity consumption per lumen (kW/lux); hr is the hours of lighting (considered as an average of 8 hours); light is the illumination demand (lux/m^2); and A_{FU} is the functional area (m^2).

4. Quantifying uncertainty and variability sources

The Monte Carlo simulation was used in this study to propagate the uncertainty and variability sources using Crystal Ball add-on in Excel. To better analyze the system, we computed the contribution of the sources to the variance of the results in two level of parameters, e.g. temperature variation, and components of life cycle stages, e.g. UHI effect.
Moreover, we divided the uncertainty and variability sources of this case study to the following three categories:

a) Parameter uncertainty due to data quality

It is the most conventional type of uncertainty that has been studied in LCA studies. This type of uncertainty is related to the quality of data used as a proxy for the unit processes in various life cycle stages. The pedigree matrix has been used to convert the qualitative judgments of obtained data into numerical values considering five different criteria, namely reliability, completeness, and temporal, geographical and technological correlation [102]. For each criterion, an uncertainty factor is calculated by analyzing data from various sources.

The variance (σ) of the parameter distributions (i.e., commonly, a lognormal distribution) is calculated based on Eq. (18):

$$\sigma^2 = \sum_{n=1}^{6} \sigma_n^2 \qquad \text{Eq. (18)}$$

where σ_1 to σ_5 are the uncertainty factors (variance) of reliability, completeness, temporal correlation, geographical correlation, and technological correlation of normal distributions to the underlying the lognormal distribution assigned to each process, respectively. In the next step, we calculated the mean and variance values of the lognormal distribution using the characteristics of the normal distribution obtained from Eq. (13). In addition, a basic uncertainty factor (σ_6) is also considered represents an environmental flow to the technosphere or emissions) [103].

b) Model uncertainty due to use phase modeling

Rather than the data quality, there are other sources of uncertainty in the calculation of life cycle impacts. In this study, we separately analyzed the uncertainty of modeling constant used, particularly in use phase components. This uncertainty is generally explained in the literature as measurement error in physical constants or modeled relationships [104, 105]. We used the information provided in previous studies to define the standard deviation of these constants. To maintain consistency, we use log-normal distributions even for constants that have percentage values since the mean and standard deviation values are significantly smaller than one, so the probability of sampling values close to one is essentially zero.

c) Variability in technological, temporal, and geographical

While the variability comes from inherent changes in the real-world (e.g., true differences in production technologies, times or regions), the uncertainty sources are attributed to simplification of reality, the introduction of subjective choices or lack of precision in LCA calculation. Variation of parameters may not have a clear representative value or distribution (i.e. does not follow a specific pattern). Therefore, to avoid overestimating the possible ranges, value and model domain parameters should be characterized using an extensive range with equal probability, such as uniform distribution [106, 107].

We quantified the uncertainty characterizations using the ecoinvent pedigree matrix methodology [106, 107]. As explained by Gregory et al. [108], empirical parameters, such as inventory quantities, comprise measurable positive values. According to the LCA literature and to be coherent with the pedigree matrix, the log-normal probability distribution is considered for the inventory quantities. The calculation of the standard deviation of the normal distribution underlying each log-normal distribution is described in Gregory et al [108]. It should be noted that the same approach was not followed to quantify the frequency distribution of the variability sources since a frequency distribution is to do with historical measurements rather than the quality of the input data. We obtained the frequency distributions of the variability sources from the historically available data in the first step. The use of uniform distribution (through the identification of minimum and maximum limits of the parameters) was the second attempt when we were unable to decide which values within this range are more likely to occur than others. Although the uniform distribution is considered as an alternative for the log-normal distribution in CMLCA and ecoinvent [109], it has the risk to be an excessive oversimplification of the variability results. Future research can explore this topic.

5. Contribution analysis results

5.1. Dynamic climate change contribution results

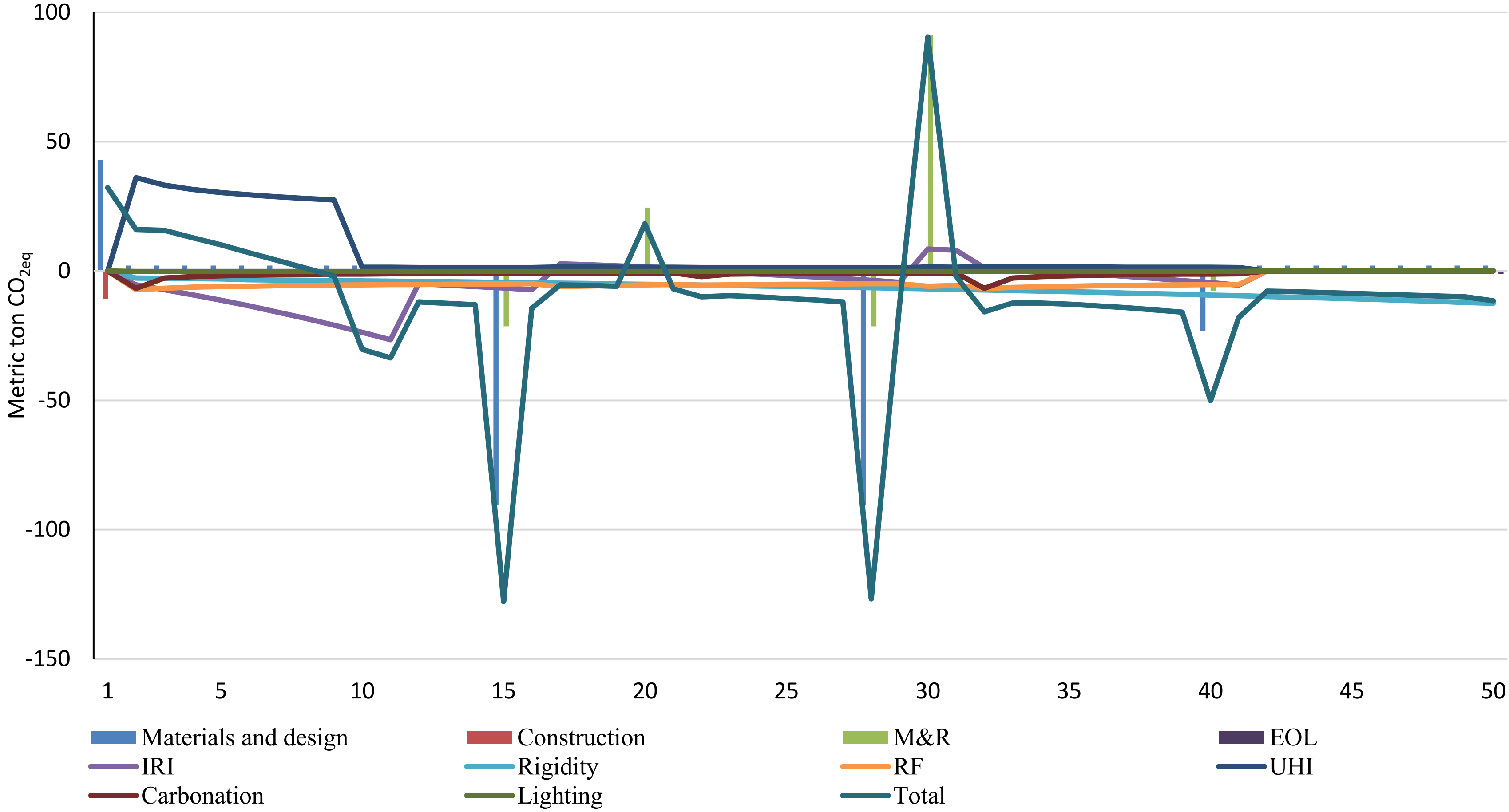

Figure A3.22. Time-dependent contribution results of climate change category

5.2. Dynamic human Health contribution results

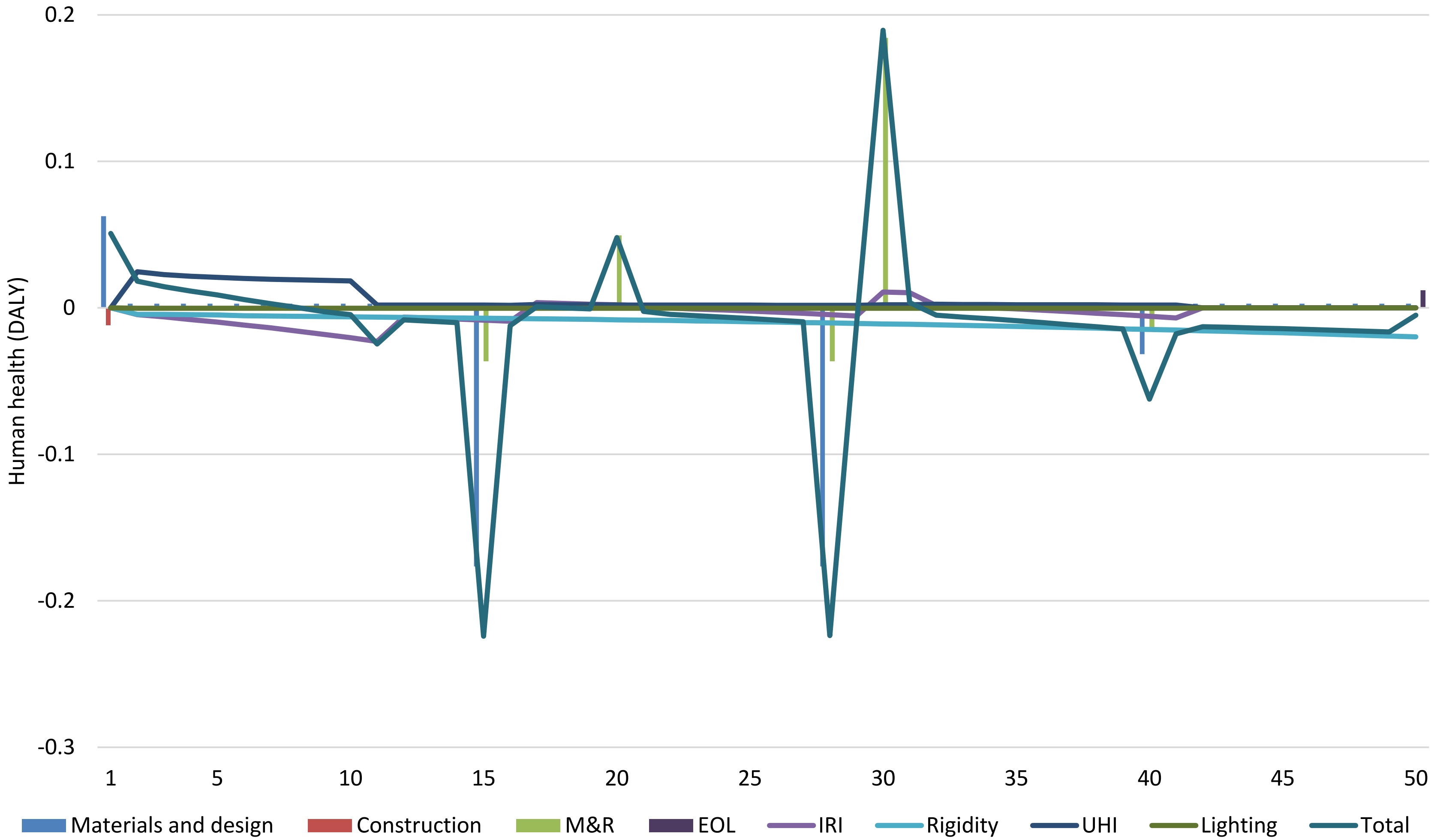

Figure A3.23. Time-dependent contribution results of human health category

5.3. Dynamic contribution results of ecosystem quality

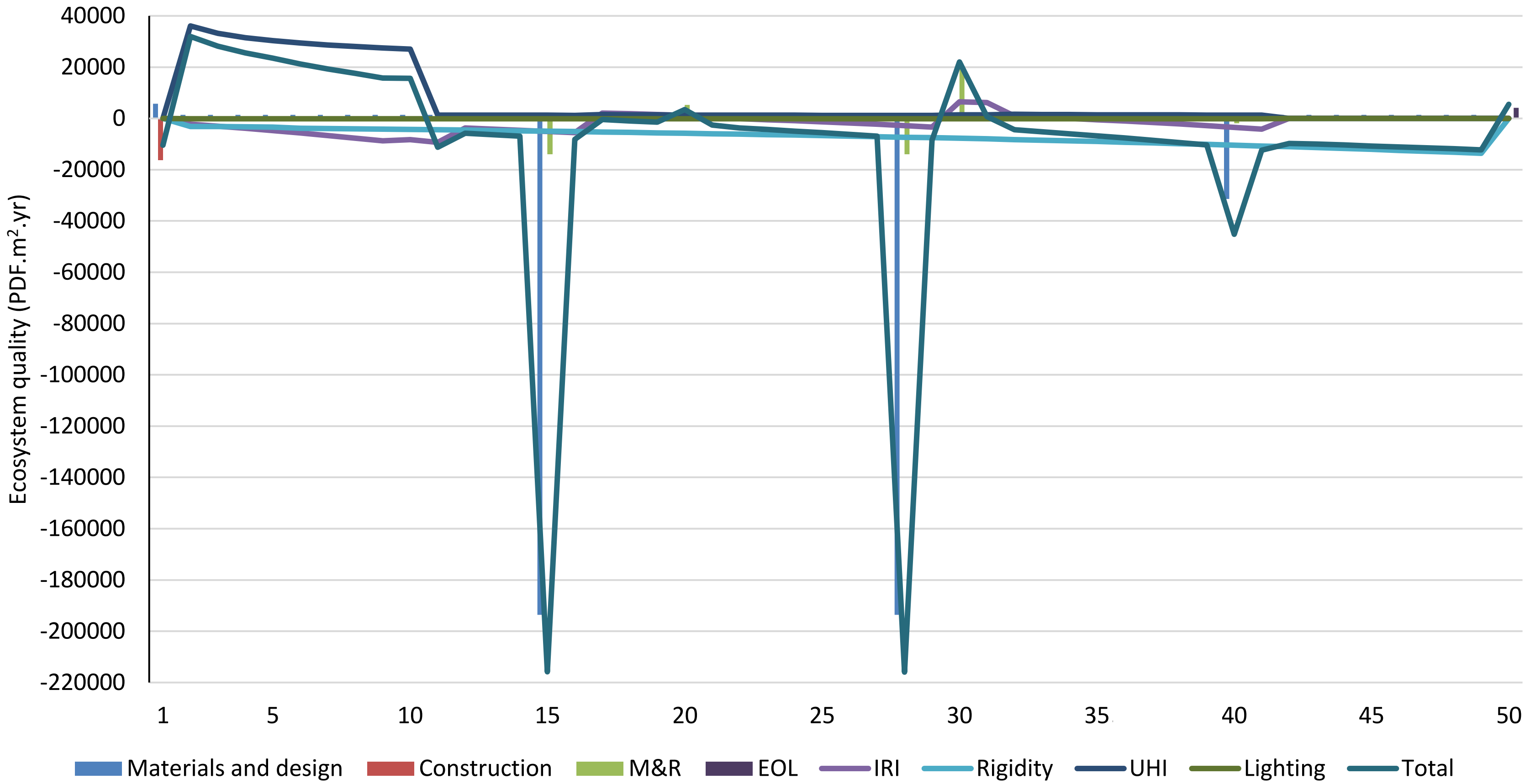

Figure A3.24. Time-dependent contribution and base-case results of ecosystem quality category

5.4. Dynamic resources contribution results

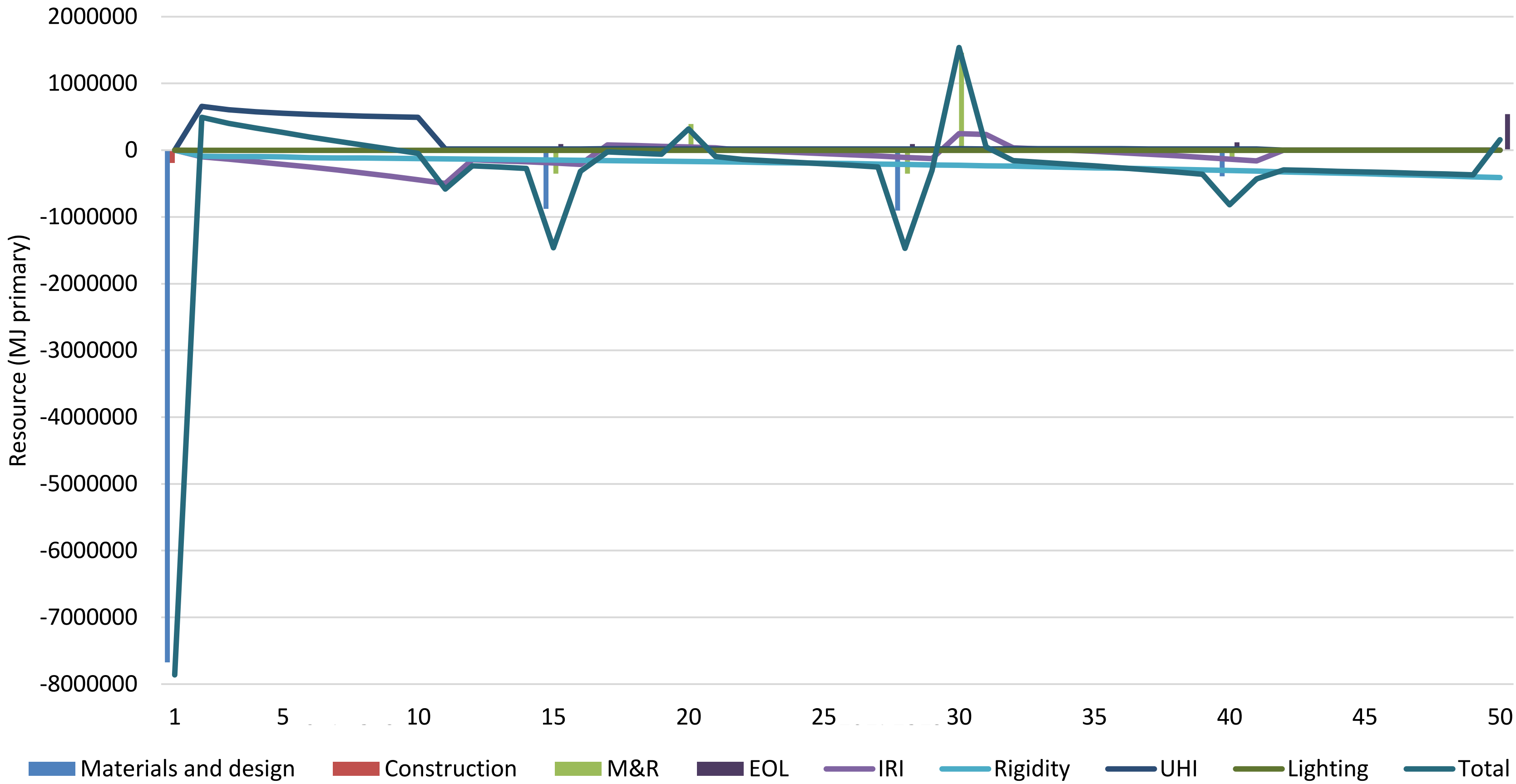

Figure A3.25. Time-dependent contribution and base-case results of resources category

5.5. Total contribution results of four damage categories

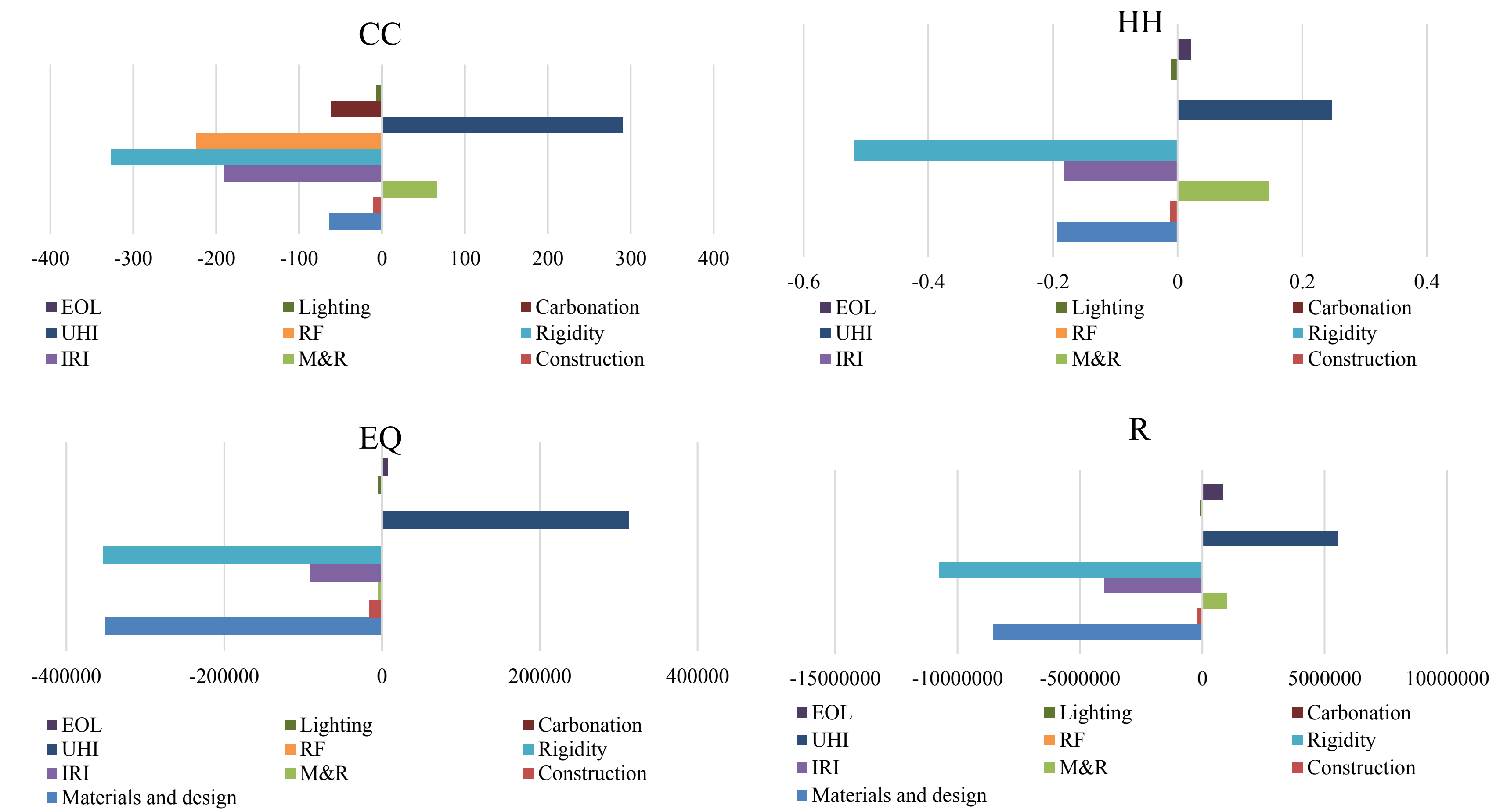

Figure A3.26. Total contribution of life cycle phases in consequences of shifting from BAU to ALT scenario (CC=Climate change; HH= Human health; EQ= Ecosystem quality; R= Resources)

5.6. Dynamic results of four major GHGs

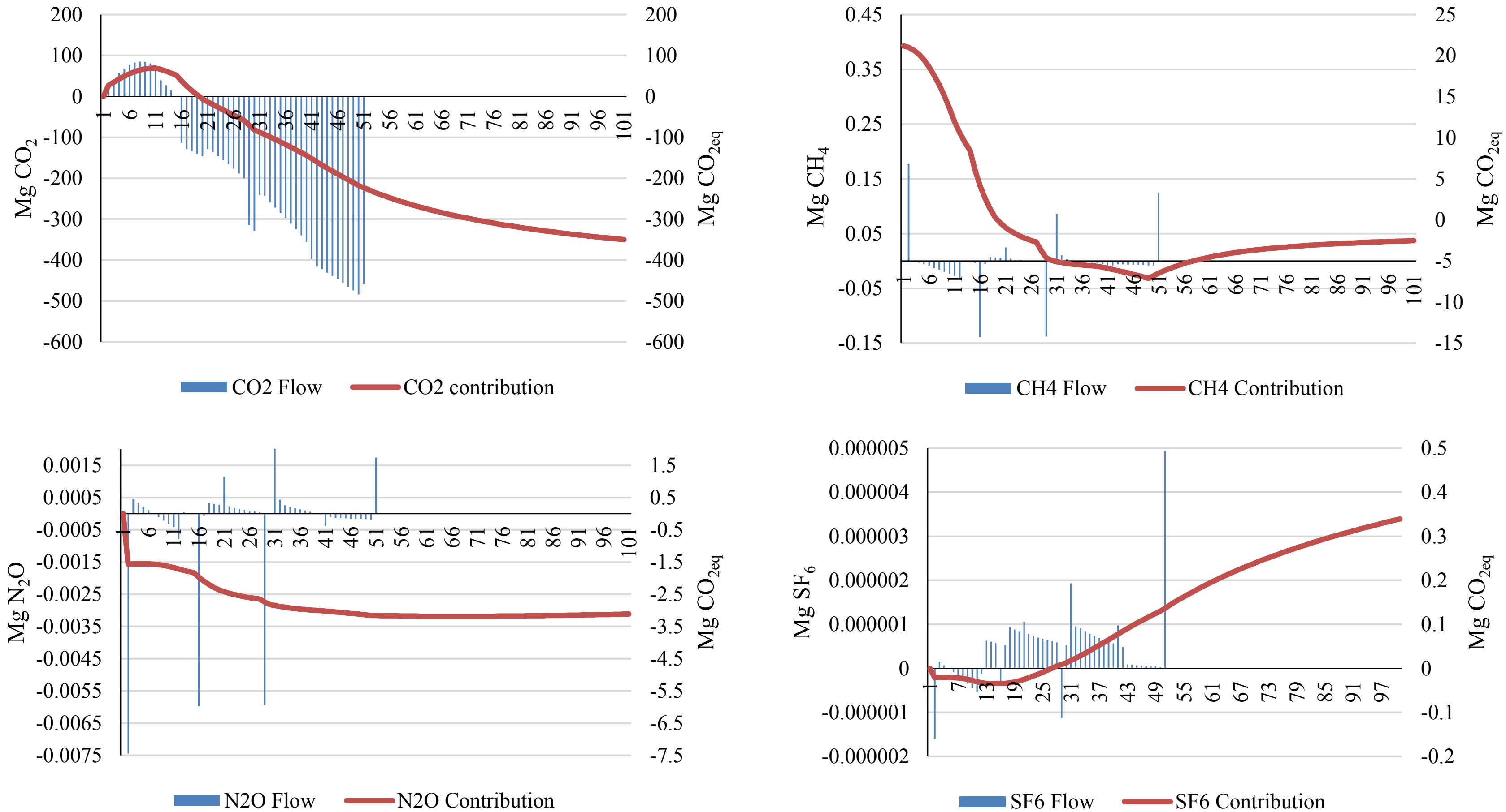

Figure A3.27. Time-dependent cumulative emissions and contribution of four major greenhouse gases to climate change results

5.7. The contribution of life-cycle components to the variance of uncertainty results

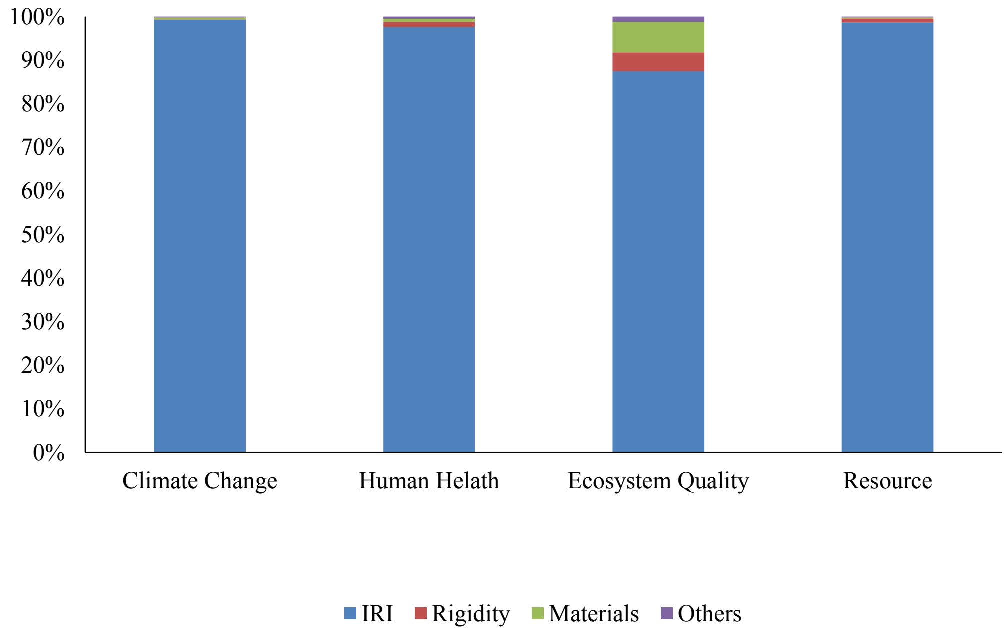

Figure A3.28. The contribution of life-cycle components to the variance of each damage category

6. Sensitivity analysis results

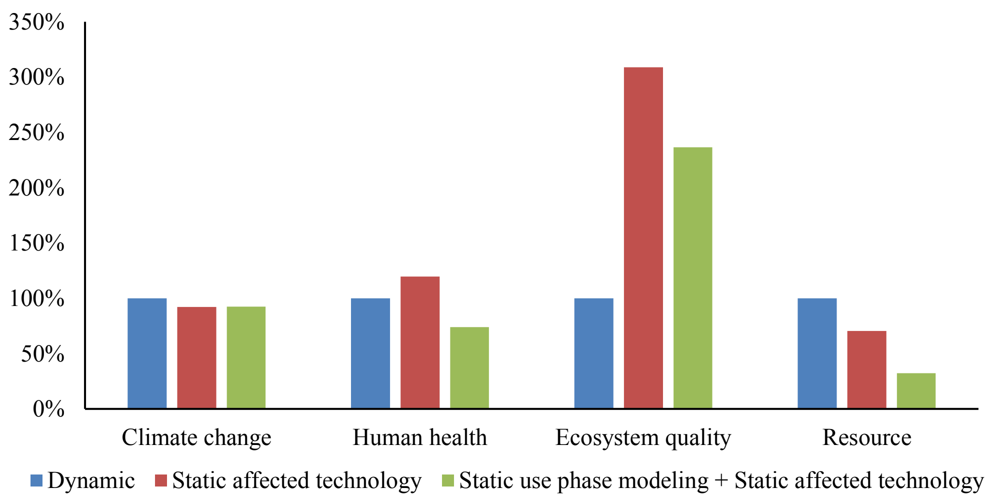

Figure A3.29. Comparison of static and dynamic inventory results (Static characterization factors were used for all the scenarios. Normalized results more than 100% show an overestimation in the environmental credits given to the substitution of BAU with ALT and vice versa. In static affected technology scenario, we considered similar modeling framework to dynamic except that we only linked the demand to long-term affected technologies. In static use phase modeling and static affected technology, in addition to isolating the affected supplier to long-term technology, we computed the use phase modeling by static inputs. List of input parameters is available in Appendix 4, Table A4.1).

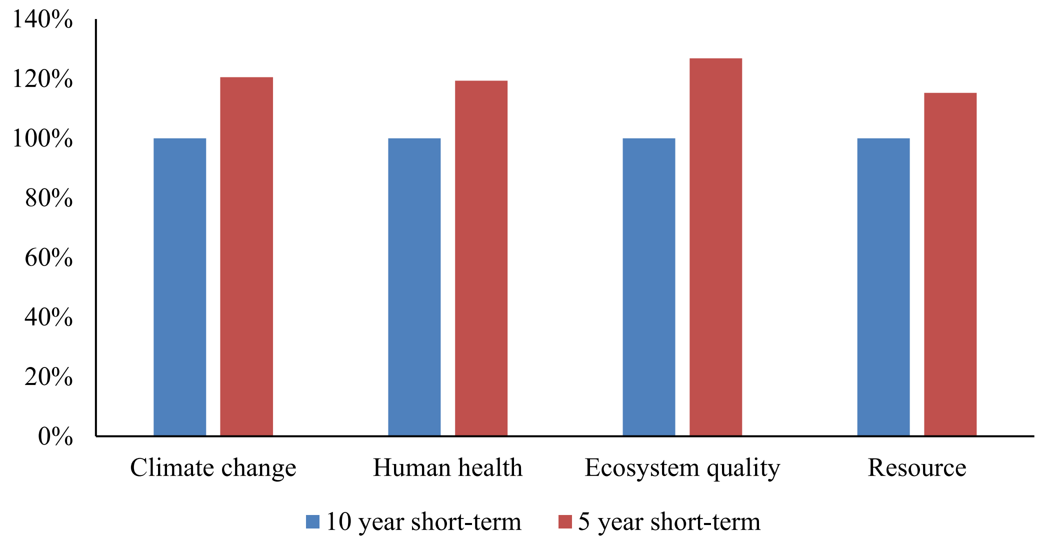

Figure A3.30. Sensitivity analysis of the dynamic vs static inventory and short-term period of 5 and 10 years

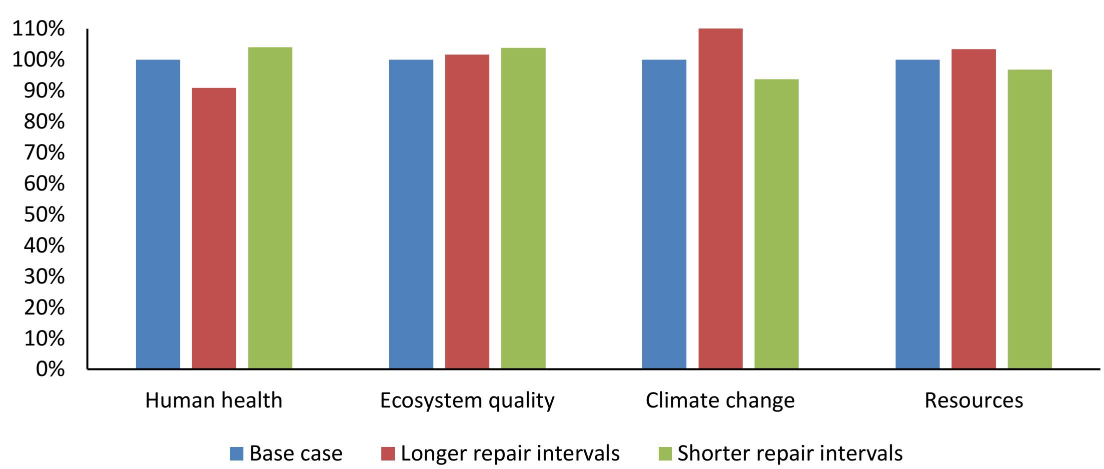

Figure A3.31. Sensitivity analysis of the increasing and decreasing the intervals of repair schedules for two years

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Appendix 4.

Inputs data and uncertainty parameters for Assessing the individual and combined effects of uncertainty and variability sources in comparative LCA of pavements

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Table A4.1. Unprecedented input parameters in dynamic consequential inventory and comparison with static consequential inventory

Parameter	Dynamic approach	Static approach
Weather Temperature (Rigidity and Urban heat island effect)	Average monthly	Average yearly
Elasticity of passenger car fuel efficiency (IRI)	Included	Not included
Improvement in car fuel efficiency (IRI and Rigidity)	Included	Not included
Average CO_2 airborne fraction	Yearly disaggregated	Aggregated
Time evolution of asphalt and concrete albedos	Included	Not included
Affected technologies and processes	Short and long-terms	Long-term
Time dependency of Concrete carbonation rate	Included	Not included
Variation in lane traffic vehicle types	Considered	Uniform average traffic for lanes
Solar radiation	Average monthly	Average yearly

Table A4.2. Concrete and asphalt input data and variability (Materials, Construction, M&R and End of Life stages)

Process	Base value data source	Variability data source	Distribution	Base value	Min	Max
Concrete lifetime (Years)	Local transportation report [1]	Emprical	Uniform	50	45	55
Portland cement mass in concrete (kg/m^3)	Empirical	Emprical	Uniform	332.5	297.5	350
Water mass in concrete (kg/m^3)	Empirical	Emprical	Uniform	140	132	165
Gravel mass in concrete (kg/m^3)	Empirical	Emprical	Uniform	960	960	970
Sand mass in concrete (kg/m^3)	Empirical	Emprical	Uniform	945	945	955
Concrete modulus of elasticity (MPa)	MEDPG	[2]	Uniform	20000	18500	21500
Asphalt modules of elasticity (MPa)	MEDPG	[3]	Uniform	2000	1820	2180
Interground limestone mass (kg/m^3)	Empirical	[4]	Uniform	17.5	0	52.5
Joint restoration	Stripple (2001)	-	-	Constant		
Concrete sealing machine	Stripple (2001)	-	-	Constant		
Concrete slip form paver, Wirtgen SP25	Producer catalog (Wirtgen website Accessed by 16/12/2015)	-	-	Constant		
Concrete surface milling, Dynapac PL2000	Producer catalog (Dynapac Website Accessed by 16/12/2015)	Emprical	Discrete Uniform	3	4	5

Asphalt overlay thickness used in concrete repair (m)	Local transportation report [1]	Emprical	Uniform	0.05	0	0.1
Concrete maintenance salt (kg/year)	Local transportation report [1, 5]	-	-	28500		
Percentage of repaired concrete joint (%)	Local transportation report [1]	Emprical	Uniform	125	100	150
Concrete rubblization, Badger 8600	Producer catalog [6]	-	-	Constant		
Recyclable concrete materials at end of life	Government document [5]	[5]	Uniform	0.5	0	0.6
Dowel bar length (m)	MEDPG		-	0.46		
Number of dowel bars in one slab	MEDPG	-	-	11		
Dowel bar weight per meter length (kg/m)	MEDPG	-	-	8.83		
Tie bar Length (m)	MEDPG	-	-	0.75		
Tie bar numbers in one slab	Empirical	-	-	6		
Number of Concrete slabs in 1 km	Empirical	-	-	200		
Asphalt lifetime (Years)	Local transportation report [1]	Emprical	Uniform	49	44	54
Bitumen mass asphalt (kg/m^3)	Empirical	Emprical	Uniform	125	100	150
Gravel mass asphalt (kg/m^3)	Empirical	Emprical	Uniform	1220	1210	1230

Sand mass in asphalt (kg/m^3)	Empirical	Emprical	Uniform	1140	1120	1150
Base and sub-base materials excavation equipment	Athena report [8, 9]	-	-	Constant		
Bitumen mass in asphalt emulsion (kg/m^3)	Empirical	-	-	Constant		
Emulsifier mass in asphalt emulsion (kg/m^3)	Empirical	-	-	Constant		
Water mass in asphalt emulsion (kg/m^3)	Empirical	-	-	Constant		
Sand in asphalt emulsion (kg/m^3)	Empirical	-	-	Constant		
Asphalt production (at plant)	Empirical	-	-	Constant		
Asphalt paver layer times	Empirical	[10]	Discrete Uniform	2	3	5
Soil compaction, Dynapac CA 151D	Producer catalogue [11]	-	-	Constant		
Asphalt compaction, Dynapac CC 122	Producer catalogue [12]	[10]	Discrete Uniform	3	4	5
Asphalt paver, Dynapac F12	Producer catalog [12]	-	-	Constant		
Asphalt surface milling, Wirtgen W 2200	Producer catalog [13]	-	-	Constant		
Asphalt thickness used in asphalt repair (m)	Local transportation report [1]	Emprical	Uniform	0.14	0.12	0.16

Asphalt repairing number of milling	Local transportation report [1]	[10]	Uniform	4	3	5
Asphalt maintenance salt (kg)	Literature [5]	-	-	20000		
Recyclable asphalt materials at end of life	Literature [7]	Emprical	Uniform	0.6	0	0.8

Table A4.3. Concrete and asphalt input data and variability (use phase)

Process	Base value data source	Variability data source	Distribution	Base value	Min	Max
Passenger car fuel economy (km/lit)	Government data [14]	[15]	Uniform	12.05	5.55	22.72
Single unit fuel economy (km/lit)	Government data [16]	[16]	Uniform	4.09	3.8	4.72
Multiple unit fuel economy (km/lit)	Government data [16]	[16]	Uniform	2.87	2.59	3.13
Fuel efficiency rebound effect	[17]	[17]	Uniform	11%	0	26%
January Weather temperature (◦C)	Government data [18]	[18]	Uniform	-11.5	-16.5	-6.5
February Weather temperature (◦C)			Uniform	-9.5	-14.8	-4.3
March Weather temperature (◦C)			Uniform	-3.6	-8.5	1.3
April Weather temperature (◦C)			Uniform	5.4	0	10.8
May Weather temperature (◦C)			Uniform	12.4	6.3	18.5
June Weather temperature (◦C)			Uniform	17.3	11.4	23.4
July Weather temperature (◦C)			Uniform	19.8	14	25.7
August Weather temperature (◦C)			Uniform	18.7	12.7	24.7
September Weather temperature (◦C)			Uniform	14.1	8.1	19.9

October Weather temperature (◦C)			Uniform	7.3	2	12.5
November Weather temperature (◦C)			Uniform	0.6	-3.4	4.7
December Weather temperature (◦C)			Uniform	-7.1	-11.5	-2.7
Incident solar radiation (W/m^2)	[19]	[19]	Uniform	CAFT		
Albedo of Concrete α_c	[20]	[21]	Uniform	CAFT		
Albedo of Asphalt α_a	[22, 23]		Uniform	CAFT		
Percentage of homes that have AC	[24]	-	Constant	42%		
Percentage of pavement effective in UHI (urban highways)	[25]	-	Constant	61%		
Urban area population percentage	[26]	-	Constant	81%		
Monthly Change in temperature due to a 0.01 change in albedo (◦C)	[27, 28]	[29-31]	Uniform	0.1	0.02	0.2
Global solar radiation (W/m^2)	[19]	[19]	Uniform	CAFT		
Cooling comfort temperature – awake time (◦C)	[24]	[24]	Discrete non-uniform	21.9	-	-
Cooling comfort temperature – asleep time (◦C)	[24]	[24]	Discrete non-uniform	21.8	-	-
Warming comfort	[32]	[32]	Uniform	21	20	22

temperature – awake time (◦C)						
Warming comfort temperature – asleep time (◦C)	[32]	[32]	Uniform	17	16	18
Carbonation rate	[33]	[33]	Uniform	1	0.75	1.5

Table A4.4. Concrete and asphalt input data and uncertainty

Process	Base value data source	Uncertainty data source	Distribution	Base Value
IRI estimation	MEDPG	[34]	Lognormal	CAFT
Traffic Growth	Empirical	[35]	Lognormal	3%
Atmospheric transmittance factor	[36]	[37]	Lognormal	CAFT
$RFCO_2$ (W/m^2)	[36]	[38]	Lognormal	1.1013
Regression coefficients p_{ij} for ECF of the pavement flexibility	[39, 40]	[40]	Lognormal	-1.918, -0.4123, -0.06942, -0.009575, 4.487, -1.802, 0.2153, 0.0203, -19.54, 4.014, -0.8618, 0.04669, 59.58, -4.628, 0.7344, -92.51, 1.375, 56.23
Albedo of Concrete α_c	[20]	[21]	Lognormal	CAFT
Albedo of Asphalt α_a	[41]		Lognormal	CAFT
Electricity consumption due to the change in winter temperature dE/dTw (kWh/◦C)	DOE 2.1E-133	DOE 2.1E-133	lognormal	10.41
Electricity consumption due to the change in summer temperature dE/dTw (kWh/◦C)	DOE 2.1E-133	DOE 2.1E-133	lognormal	3.05

Inventory name	Emissions source (unit process)	Indicator Score					Basic uncertainty
		Reliability	Completeness	Temporal Representativeness	Geographical Representativeness	Technological Representativeness	
Reinforcing Steel	Reinforcing steel [GLO]| production | Conseq, U	1	1	2	2	2	0.0006
Pig Iron	Pig iron [GLO]| production | Conseq, U	1	1	2	2	2	0.0006
Low alloyed steel	Steel, low-alloyed [GLO]| steel production, converter, low-alloyed | Conseq, U	1	1	2	2	2	0.0006
Unalloyed steel	Steel, unalloyed [GLO]| steel production, converter, unalloyed | Conseq, U	1	1	2	2	2	0.0006
Steel rolling	Hot rolling, steel [GLO] | processing | Conseq, U	1	1	2	2	2	0.0006
Concrete Sand	Sand [GLO]| gravel and quarry operation | Consequential, U	1	1	2	2	1	0.0006
Concrete Gravel	Gravel, crushed [CA-QC] | production | Conseq, U	1	1	2	1	1	0.0006
Tap Water	Tap water [CA-QC] | tap water production, underground water without treatment | Conseq, U	1	2	1	1	1	0.0006

Waste water at batching plant	Wastewater from concrete production [GLO] | treatment of, capacity 5E9l/year | Conseq, U	1	1	2	2	3	0.0006
Cement	Cement, Portland [CA-QC]| production | Conseq, U	1	1	2	1	1	0.0006
Clinker	Clinker [CA-QC] | production | Conseq, U	1	1	2	1	1	0.0006
Tire-derived fuel combustion	(United States Environmental Protection Agency 1997)	1	3	5	3	4	0.0006
Coal combustion	Heat, district or industrial, other than natural gas [GLO]| heat production, at hard coal industrial furnace 1-10MW | Conseq, U	1	1	2	2	3	0.0006
Biomass combustion	Heat, district or industrial, other than natural gas [GLO]| heat production, softwood chips from forest, at furnace 1000kW | Conseq, U	1	1	2	2	3	0.0006
Superplasticizer	(EFCA (European Federation of Concrete Admixture Associations) 2006)	1	2	4	4	1	0.0006

Limestone	Lime [GLO] | production, milled, loose | Conseq, U	1	1	2	2	1	0.0006
Mastic Asphalt	Mastic asphalt [GLO]| production | Conseq, U	1	1	2	2	1	0.0006
Concrete batching plant	Concrete, 30-32MPa [CA-QC]| concrete production 30-32MPa, RNA only | Conseq, U	1	1	2	1	1	0.3
Crude oil refinery	Petroleum refinery operation [GLO]| Extracted from ecoeditor and data was replaced by "Conseq, U" background processes	1	1	4	3	2	0.0006
Crude oil extraction	Petroleum [CA-AB]| petroleum and gas production, on-shore | Conseq, U	1	1	2	1	1	0.0006
Bioasphalt	(Steele, Puettmann et al. 2012)	1	1	3	2	1	0.0006
Asphalt Sand	Sand [GLO]| gravel and quarry operation | Consequential, U	1	1	2	2	1	0.0006
Asphalt Gravel	Gravel, crushed [CA-QC] | production | Conseq, U	1	1	2	1	2	0.0006
Hot mix asphalt plant natural gas	Heat, district or industrial, natural gas [GLO]| heat production, natural	1	1	2	2	1	0.0006

	gas, at industrial furnace >100kW | Conseq, U						
Hot mix asphalt plant heavy fuel oil	Heat, district or industrial, other than natural gas [CH]| heat production, heavy fuel oil, at industrial furnace 1MW | Conseq, U	1	1	2	3	2	0.0006
Hot mix asphalt plant electricity	Electricity, medium voltage [CA-QC]| market for | Conseq, U	1	1	2	1	1	0.0006
Base and sub-base materials Fuel	Diesel, burned in building machine [GLO]| market for | Conseq, U	1	1	3	3	1	0.0006
Base and sub-base materials Electricity	Electricity, medium voltage [CA-QC]| market for | Conseq, U	1	1	2	1	1	0.0006
Construction and maintenance Equipment	Building machine [GLO]| market for | Conseq, U	1	1	2	2	2	0.3
De-icing salt	Sodium chloride, powder [GLO] | market for | Conseq, U	1	1	2	2	1	0.0006
Diesel for Construction and maintenance Equipment	Diesel, burned in building machine [GLO]| market for | Conseq, U	1	1	2	2	1	0.0006
Transport	Transport, freight, lorry 16-32 metric ton,	1	1	2	2	2	0.12

	EURO3 [GLO]| market for | Conseq, U						
Diesel for heavy trucks	Transport, freight, lorry 16-32 metric ton, EURO3 [GLO]| market for | Conseq, U	1	1	2	2	1	0.12
Diesel for medium trucks	Transport, freight, lorry 3.5-7.5 metric ton, EURO4 [GLO]| Conseq, U	1	1	2	2	1	0.12
Gasoline for light vehicles	Transport, passenger car, medium size, petrol, EURO 4 [GLO]| Conseq, U	1	1	2	2	1	0.12
Household electricity	Electricity, medium voltage [CA-QC] | market for | Conseq, U	1	1	2	1	1	0.0006
Road lighting	Electricity, medium voltage [CA-QC] | market for | Conseq, U	1	1	2	1	1	0.0006
Landfilling of concrete	Waste concrete [GLO]| market for | Conseq, U	1	1	2	2	2	0.0006
Landfilling of asphalt	Waste asphalt [GLO]| market for | Alloc Rec, U	1	1	2	2	2	0.0006
Carbon dioxide to air	-	-	-	-	-	-	0.0006

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